GEOHYDROLOGICAL IMPLICATIONS OF CLIMATE CHANGE ON WATER RESOURCE DEVELOPMENT

by

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A contract report
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Submitted to

U.S. Army Coastal Engineering Research Center
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PROLOGUE

In spite of the paramount importance of water to the nation's economy and general well-being, comparatively little attention has been given to the effects of climatic variability on the managment of this valuable resource. In general, climatic variability is most important in areas where demand approaches supply. Thus the most severe impacts are likely in arid climates where the supply is limited and metropolitan areas where the demand is great. In high demand areas there is keen competition for domestic, agricultural, industrial and power generation purposes. Some of these consume water; others use water and return it to the source although quality is often degraded in the process. When supply and demand are essentially equal, a slight climatic change that reduces the supply can have serious economic and social impacts. In contrast, the same variation in a humid region may have only minor impacts because the supply exceeds the demand by a comfortable margin.

The conterminous United States is clearly divided around the 100th meridian into a semi-arid western portion (except the extreme northwestern corner) and a more humid eastern portion. In the western part, evapotranspiration is greater than the average annual precipitation although the difference varies from region to region. This same part of our nation includes some of the most intensively developed agricultural land and fastest growing metropolitan centers, both competing for existing water supplies. Development of energy resources such as coal, hydro power and oil shale is also intense and water demanding. The result is the demand for water is fast approaching that which is available under the present climatic state.

The frequency with which extreme events such as floods and droughts occur points out the dangers in dealing with averages. In long term records, periods of deficits and excesses tend to be more extended and extreme than would be expected in a random process. Thus, when considering the hydrologic effects of climate it is essential that both the high (short-term) and low (long-term) frequency variations are considered.

High frequency variations (meterologic) are self-evident since they occur on a year-to-year basis. In contrast, low frequency changes (climatic) are more subtle and more difficult to interpret in a management context. However, the low frequency changes are important. For instance, the climatic optimum which occurred about 6,000 B.P. represented a 1°C. to 2°C. increase in temperature. This relatively small change is believed responsible for the eastern extension of the western grasslands through Iowa and Illinois and into Indiana and Ohio. There is ample evidence of more recent low frequency variations -- the warming trend durirg the first half of the present century followed by a cooling trend during the past two decades. Thus, such variations have occurred in the past and will continue in the future. Climate results from the interactions of many dynamic forces and it is difficult to perceive a steady state in the future.

Future trends are complicated by an added parameter - mans' activities. Climatologists are at odds over whether we will experience a warming trend due to the ever-increasing carbon dioxide levels or cooling because of the large amounts of particulate matter injected into the atmosphere by industrial and other activities. Our purpose here is not to debate the causes of future climatic variations but to consider the need for their inclusion in long-range water resources planning processes, especially for the next 50 years.

The U.S. Army Corps of Engineers has attempted to address the question of how future climatic changes might affect water resource management in the United States. This has been done through a series of contracts, each addressing a different aspect of the problem. Our contribution to the overall project has been to consider and conjecture as to the hydroclimatological effects of the following four climatic change scenarios:

1. An increase in mean annual temperature of up to 2 degrees Celsius, with an associated decrease in mean annual precipitation of 10 percent (warmer and drier).

2. A decrease in mean annual temperature of up to 2 degrees Celsius with an associated increase in annual precipitation of 10 percent (cooler and wetter).

3. An increase in mean annual temperature of up to 2 degrees Celsius associated with an increase in total annual precipitation of 10 percent (warmer and wetter).

4. A decrease in mean annual temperature of up to 2 degrees Celsius with an associated decrease in total annual precipitation of 10 percent (cooler and drier).

In most instances we have tentatively determined that only scenarios 1 (warmer and drier) and 2 (cooler and wetter) would be important, since for scenarios 3 and 4 the net increase or decrease in temperature would likewise change evapotranspiration rates and essentially offset the gain or loss from changes in precipitation.

We reasoned that future climatic variation would probably not be uniform throughout the nation and any climatic effect on hydrologic processes, especially surface runoff, would likewise not be uniform. The effects of the various scenarios were, therefore, considered for each of the 18 Water Resource Regions developed by the Water Resources Council. Each region has been described from the standpoint of its geology, topography, land use and existing and projected demands upon water resources. A regional speculative impact matrix was developed for each scenario determined to be nontrivial. The various cells of the matrix relate the elements of streamflow characteristics that are affected by climatic variability to their effect on water supply parameters including quantity, quality and existing engineering structures and developments.

We hasten to point out an inherent weakness in our approach in that the climatic changes were considered only on an annual rather than on a seasonal basis. The effect of a 10 percent increase in precipitation would be considerably different if most of the change occurred during the summer rather than the winter months, or *vice versa*. The same is true for temperature. However, contract time did not permit a more detailed analysis.

Preliminary to the above, an introductory section was prepared that considered evidence of past climatic change, indications of long-term climatic variability, and the effects on streamflow. The use of proxy data in extending hydrologic and climatic records backward in time was also considered. A literature review evaluating and appraising methods currently being used to generate synthetic streamflow sequences is also included.

Throughout the discussion we have emphasized the point that the period covered by historic hydrologic records (usually relatively short in duration) is not necessarily a random sample of the infinite number of events that have occurred in the past. For this reason statistical treatment of such data must be done with some degree of caution as errors in interpretation can occur that may materially affect water resources planning.

We wish to emphasize the fact that our speculations and conjectures regarding the effects of climatic variability on hydrologic processes are just that and are based on experience, the work of others, and our own best judgements. Our opinions will be acceptable to some and unacceptable to others.

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May 15, 1979

ABSTRACT

One of the basic assumptions in hydrology is that hydrologic time series are stationary in the sense that the probability distribution of a series can be determined from a finite sample and that it will not change with time. This assumption implies that climate which is an integral part of all hydrologic series is stationary with time. The fact is that climate is nonstationary and this non-stationarity varies from region to region. The objective of this study is to evaluate the known physical state of hydrologic processes in each of the 18 Water Resource Regions for the conterminous United States as outlined by the Water Resources Council and to speculate on the response of the system to superimposed climate variability. Four climate scenarios are evaluated encompassing all combinations of a 2°C. change in mean annual temperature with an accompanying 10 percent change in total annual precipitation. The technique used involves estimated change in mean annual runoff with respect to that of the present using empirically developed curves that relate weighted mean annual temperatures to mean annual precipitation and runoff. An evaluation of presently available models and techniques for incorporating climate variability into synthetic hydrologic traces is also discussed. Tree-ring data series are mentioned as a possible way of investigating regional climatic variability on hydrologic responses.

The region-by-region evaluation of climatic change impacts indicates that a change toward a warmer and drier climate (scenario 1) would have the greatest effect on a nation-wide basis. These effects are largely adverse and the most severe impact would be in the water deficient regions west of the Mississippi River. In contrast, mostly beneficial effects would accrue from a change to cooler and wetter conditions (scenario 2). The greatest positive effects would be in the dry western regions; some negative effects would result from increased flooding on most major river systems and their tributaries, especially eastward from the Missouri and Mississippi Rivers. The effect of warmer and wetter (scenario 3) and cooler and drier (scenario 4) climatic variations on annual runoff are conjectured to be trivial in most regions. Only in the Upper Colorado River Region did scenario 3 prove to be non-trivial on a region wide basis.

Our impact analysis indicates all regions would be adversely affected by a warmer and drier climatic change. In one region, the South Atlantic-Gulf, the impact is considered negligible. The adverse impacts were considered minor in the New England, Ohio, Souris-Red-Rainy, Great Basin, Pacific Northwest, and Lower Mississippi Regions. Moderate impacts are postulated for the Mid-Atlantic, Great Lakes, Tennessee, and Upper Mississippi. Major changes in the response of the water resources system are postulated for the Arkansas-White-Red, Texas Gulf, Rio Grande, Upper Colorado, Lower Colorado, California and Missouri Regions. Even under warmer and drier conditions, total runoff from the Pacific Northwest Region is greater than the present combined total annual runoff from the California, Great Basin, Lower Colorado and Upper Colorado Regions. In fact, the Pacific Northwest Region is the only region in the western United States that presently appears to have a water supply surplus.

For a cooler and wetter climatic variation (scenario 2) adverse effects are predicted for some regions, although the national impact would be mostly beneficial. Adversely affected regions are the South Atlantic-Gulf, the Lower Mississippi and the Great Basin. The remaining fifteen regions would be beneficially affected, although the New England, Mid-Atlantic, Great Lakes, Souris-Red-Rainy and the Pacific Northwest Regions fall into the negligible category. An apparently beneficial impact would be felt by the Ohio, Tennessee, Upper Mississippi, Missouri, Upper Colorado, Arkansas-White-Red, Texas Gulf, Rio Grande, Lower Colorado and California Regions, although there would be increased flooding in five of these.

Several regions where water is currently abundant with respect to demand, would experience only negligible or minor impacts regardless of whether warmer and drier (scenario 1) or cooler and wetter (scenario 2) climatic variations would occur. These include New England, South Atlantic-Gulf, Ohio, Souris-Red-Rainy, Great Basin and Pacific Northwest.

The effects of the postulated climatic changes on the total water reserve is shown by comparing the ratios of regional total reservoir capacity to mean annual runoff for the present and for warmer and drier (scenario 1) and cooler and wetter (scenario 2) climatic variations. The results show all regions east of and including the Upper and Lower Mississippi Regions would tend to fill the existing reservoir storage in 1.2 years or less regardless of whether scenario 1 or 2 climatic variations occurred. In the west, the region most affected by either change would be the Lower Colorado River Region. Under the present climatic regime and total available storage, there is enough capacity to accomodate 12+ years of mean annual regional flow, including present level of inflow. If a warmer and drier (scenario 1) variation occurred it would require nearly 19 years reservoir capacity. In the Missouri River, the present total reservoir capacity would be quite beneficial as only a little less than two years of mean flow would be required to fill to total capacity should a cooler and wetter (scenario 2) change occur; presently a little less than three years is required. If a warmer and drier (scenario 1) change occurred, a little over eight years would be required.

What are the present trends in climate? At this time, there appear to be different lines of evidence suggesting a present cooling trend over much of the Northern Hemisphere with at least one study suggesting it will continue. Some climatologists indicate that with increasing carbon-dioxide in the atmosphere, this will reverse and warming will be the dominant future trend.

Analysis of individual regional runoff series do not show any indication of trends in runoff data suggesting a uniform increase in mean annual runoff. In fact, the opposite is true. In a rather restricted segment of the western southern Rocky Mountain Region, the trend is toward reduced runoff. When the overall total streamflow of the nation is considered however, there is no apparent trend in the data.

Findings and Conclusions

1. Climate within the conterminous United States can not be considered to be time or space invariant.

2. Evidence exists that major climatic variation has occurred in the Northern Hemisphere mid-latitudes during the last 70-80 years.

3. During the period 1880-1969, average temperature for the Northern Hemisphere attained a maximum around 1940 and has decreased to about 1970. Maximum range from highest to lowest is +1 °C. During the last 5 years however, the decrease has leveled off and there has been little change.

4. General hemispheric circulation can be used to typify large scale climate and climatic variations. However, local and regional variations can and do result from the larger scale features.

5. Based on long term climatic variation as revealed by proxy records, the assumption of stationarity in hydrologic records is not in serious error when planning horizons are 10 to 20 years in duration apparently because of the slow response time of the atmosphere to different forcing functions. For periods greater than 30 years, the assumption of stationarity can be wrong and lead to serious consequences.

6. Early work incorporating large scale climatic variation into water resources planning was conducted by Langbein in the United States and Hurst in Egypt. Later work has been done by Julian and Stockton.

7. Hurst was apparently the first to quantify the long-term persistence attributed to climate in hydrologic records. Hurst's work was significant to hydrologists because he demonstrated that his findings of persistence in mean annual runoff had major ramifications on the size and operations of reservoirs. There has been much conjecture among hydrologists concerning the cause and best technique for modeling the Hurst phenomenon.

8. One technique for incorporating the so-called Hurst phenomenon into hydrologic records is to use proxy series to interpret the long term persistence. We cite an example using tree ring data to reconstruct 360+ years of July drought occurrence in the western United States. Maps were developed showing the long term frequency of occurrence of July drought and long term persistence. Greatest probability of occurrence of July drought is a band extending from the southwest to the northern Great Plains. Greatest persistence in drought, however, is a band extending from the northwest to the southern Great Plains. Long term drought persistence is greatest in the central and northern Great Plains, northern Rocky Mountains and Great Basin and the Colorado River Basin. Drought is least persistent in the extreme northwest and southeastern portion of the Nation.

9. An evaluation of current models used in hydrology to model the climatic effect reveals:

   (1). Deterministic models are: (a) either so detailed that application to various basins requires almost limitless data and complex computer programs with large storages; in application, approximations for the data tend to pollute the elegant physical detail; or (b) the number of variables are reduced by lumping or omitting them causing loss of appropriateness for general application.

   (2). The stochastic processes used to mimic the long-term persistence in runoff range from the fractional gaussian noise processes, to the first order autoregressive process and the mixed autoregressive moving average (ARMA) models. The present concensus seems to be that the first order autoregressive model is the easiest to use although it does not incorporate long term persistence. The ARMA models do incorporate persistence but the Hurst coefficient is not an explicit parameter. At this time there does not appear to be any universally applicable model for incorporating long term climatically induced variation into hydrologic series. More detailed knowledge of climatic dynamics on both large and regional scales is necessary for assessing the effect of climatic variability on the hydrologic system.

10. A region-by-region analysis of the 18 Water Resources Regions as defined by the Water Resources Council (1978) indicates that a warmer and drier change in climate (scenario 1) would have the greatest national effect on water supply. Most of this would be in the regions located west of the Mississippi River.

11. A cooler and wetter (scenario 2) climatic change would have mostly beneficial effects, again with the greatest impact being in those regions west of the Mississippi River where the present mean annual requirement/mean annual supply ratios are high.

12. Warmer and wetter (scenario 3) and cooler and drier (scenario 4) climatic changes are evaluated as being trivial in most regions. Only in the Upper Colorado Region did scenario 3 prove to be non-trivial.

13. An analysis of the ratios of projected (year 2000) mean annual requirements/mean annual supply under the present climatic state and those that would ensue if a warmer and drier (scenario 1) and cooler and wetter (scenario 2) climatic variation should occur reveals that at under the present climatic state only one region is projected to have a ratio exceeding 1.00 by the year 2000, that is the Lower Colorado Region. Others with high ratios are the Rio Grande, Upper Colorado, Missouri, California and the Texas-Gulf Regions. These results are not quite as adverse when total available surface water storage/mean annual flow ratios are also considered. For example, the Lower Colorado Region also has the greatest ratio of total reservoir storage to mean flow (12.66) which indicates 12+ years of mean annual flow are in storage when all reservoirs are full. A measure of the degree of storage - both

natural and man made - is expressed by the ratio of Q_{05}/Q_{95} for the streamflow out of the region. The smaller this value, the lower the variability of the streamflow from the region. The Lower Colorado has the lowest value of Q_{05}/Q_{95} (1.4) of all regions. These results are summarized in the following table.

Region	Present Climatic State					Scenario 1 (warmer and drier)			Scenario 2 (cooler and wetter)		
	Estimated mean annual supply (bgd)[a]	[illegible] requirement (bgd)[c]	requirement / supply	total storage / mean annual flow	Q_{05}/Q_{95} (streamflow)	Estimated mean annual supply (bgd)	total storage / mean annual flow	requirement[e] / supply	Estimated mean annual supply (bgd)	total storage / mean annual flow	requirement / supply
01. New England	78.6	1.03	0.01	0.38	2.2	56.6	0.54	0.02	108.5	0.28	0.009
02. Mid-Atlantic	81.0	3.54	0.04	0.48	2.4	53.5	0.73	0.07	115.0	0.34	0.03
03. South Atlantic Gulf	232.5	10.05	0.04	0.39	2.9	148.8	0.42	0.07	339.5	0.19	0.03
04. Great Lakes	75.3	4.69	0.06	0.27	2.3	50.5	0.41	0.09	103.2	0.20	0.04
05. Ohio	179.0[b]	4.33	0.02	0.29	2.4	111.0	0.47	0.04	256.0	0.21	0.02
06. Tennessee	41.1	1.11	0.03	0.75	1.9	25.9	1.20	0.04	56.7	0.55	0.02
07. Upper Mississippi	114.0[b]	2.66	0.02	0.27	2.9	70.7	0.51	0.04	166.4	0.18	0.02
08. Lower Mississippi	416.8[b]	5.51	0.01	0.05	3.7	291.8	0.09	0.02	571.0	0.03	0.009
09. Souris-Red-Rainy	6.1	0.47	0.07	1.72	1.4	3.4	3.11	0.14	10.2	1.03	0.05
10. Missouri	61.5	26.14	0.42	2.92	4.1	22.1	8.12	1.18	100.9	1.77	0.26
11. Arkansas-White-Red	67.7	12.03	0.18	1.32	5.5	31.1	2.41	0.39	138.8	0.66	0.09
12. Texas-Gulf	35.6	12.52	0.34	1.97	10.3	17.8	3.94	0.70	71.2	1.05	0.18
13. Rio Grande	5.3	4.80	0.87	3.58	22.0	1.3	14.2	3.69	9.5	1.99	0.51
14. Upper Colorado	13.9	11.75[d]	0.84	1.38	4.0	9.3	2.21	1.26	27.0	0.72	0.44
15. Lower Colorado	8.3[b]	9.87	1.18	12.66	1.4	3.6	18.99	2.74	14.1	4.83	0.70
16. Great Basin	13.9	4.37	0.31	0.51	3.8	7.6	0.93	0.57	25.3	0.29	0.17
17. Pacific Northwest	286.5	17.28	0.06	0.40	1.9	171.8	0.62	0.10	386.6	0.28	0.04
18. California	73.4	30.39	0.42	1.08	4.0	41.1	2.15	0.74	119.6	0.63	0.25

(a) assumes zero ground water overdraft
(b) inflow from upstream region included
(c) projected through the year 2000
(d) includes 6.70 bgd for downstream obligations
(e) assumes no increase in evapotranspiration rate from present climatic state

14. According to our speculative impact analysis, all regions would be adversely affected by a warmer and drier (scenario 1) climatic change. The degree to which each region would be affected is classified according to major, moderate, minor and negligible. The average region would suffer moderate impact according to our numerical ranking. The regions suffering a major impact from a scenario 1 climatic change are: Arkansas-White-Red, Texas-Gulf, Rio Grande, Upper Colorado, Lower Colorado, California and Missouri. As ground water sources are already heavily utilized in these 7 regions, it is not considered to be a viable alternative to surface water shortage. The South Atlantic-Gulf would be negligibly affected by a scenario 1 change primarily because of its large surface and ground water supplies. The same is true of those in the minor category: New England, Ohio, Souris-Red-Rainy, Great Basin, Pacific Northwest and Lower Mississippi Regions.

15. For cooler and wetter (scenario 2) climatic conditions, adverse effects are predicted for some regions although the national impact would be mostly beneficial with the average region falling into the minor (beneficial) category. Those adversely affected are the South Atlantic-Gulf, New England, Lower Mississippi, and Great Basin Regions. In the first three cases, the regions are presently water-rich and additional runoff would probably be adverse rather than beneficial. In the Great Basin with its large closed basins, it is assumed the additional runoff would cause inundation of large areas. The remaining 15 regions would be beneficially affected although four of these fall into the negligible category. These four are the Mid-Atlantic, Great Lakes, Souris-Red-Rainy, and Pacific Northwest Regions. An appreciable impact would be felt by ten regions although five of these would experience increased flooding.

16. Several regions would experience only negligible or minor impacts regardless of whether scenario 1 or 2 occurred. These include New England, South Atlantic-Gulf, Ohio- Souris-Red-Rainy, Great Basin and Pacific Northwest. In all of these regions water is currently abundand and although an occurrence of climatic change might create hardships, the result would not be catastrophic on a region-wide basis. But in the Arkansas-White-Red, Texas-Gulf, Rio Grande, Upper Colorado, Lower Colorado, Missouri and California Regions, the occurrence of a scenario 1 type change would possibly create region- wide economic and legal havoc and would certainly have national policy implications.

17. In the area west of the Mississippi River, a warmer and drier (scenario 1) change would require additional reservoir storage although in a few regions (e.g. the Lower Colorado) the present capacity may be excessive. In regions east of and including the Upper and Lower Mississippir Regions, the mean annual regional flow resulting from a cooler and wetter (scenario 2) change would tend to fill the total existing reservoir storage in about ½ the time required for the present mean annual flow. It appears that much additional reservoir storage would be needed in these regions primarily for flood control.

18. Projected future climatic trends are conflicting. Strong evidence exists that a mean annual cooling trend beginning in the early 1940's

has not abated. Many climatologists, however, predict that owing to mans' activities, the future trend is most likely to be toward warmer mean annual temperatures. Analysis of mean annual runoff series in the conterminous United States indicates that on a national scale there is no apparent consistent trend in mean annual runoff. However, in a rather restricted segment of the southern Rocky Mountain area, the trend is toward reduced mean annual runoff.

INTRODUCTION

Recent apparent anomalies in the usual state of climate in the northern hemishpere have led to increased interest in understanding the effects of climatic variability upon the availability, design and management of water resources. This interest is partially stimulated by the fact that in much of the western United States, the demand for water is fast approaching the natural supply. Because of this apparent convergence of supply and demand, along with multiple use conflicts and water quality problems in areas of adequate supply, it is of interest to consider the effects climatic variability may have upon the future needs of the Nation for adequate water management, be it insufficient supply or protection from flooding.

Since the early 1900's the classical approach to analyzing hydrologic data for future projections has been to fit a theoretical probability distribution function to the data. Then, knowing the function, the probabilities of future occurrences are determined based on that theoretical distribution. Many distribution functions have been used through the years. A few of the more common ones are the Gaussian (normal); the Gumbel (Extreme Value Type I); Lognormal; Pearson Type III (Gamma); Weibull; and Pareto Type I (Pearson Type IV). In applying each distribution function, it is necessary to evaluate existing data and estimate specific parameters such as the mean (1st moment), variance (2nd moment), skewness (3rd moment) and kurtosis (4th moment) and demonstrate the data fit to the theoretical distribution function. This is accomplished in several ways, although in recent years, computer programs are readily available to analyze the data and the proper distribution function. Prior to the common use of the computer, special probability paper was extensively used; if the proper function was assumed and the correct special plotting paper used, the data plotted as a straight line and probabilities of future occurrences could be determined directly from the plot.

Additional pre-analysis data preparation is sometimes used, with the most common being to transform the data to logarithms before fitting the probability distribution function. For example, present recommended procedures for determining flood recurrence intervals (USWRC, Bulletin 17A, 1977) utilize the Log Pearson Type III distribution as outlined by Beard (1962). In many cases, outliers occur in the data, that is, items that appear anomalous or inconsistent with the bulk of the data. They are the highest or lowest magnitudes in a set of data. Except for special cases, the outlier is either ignored or it is given less weight in fitting the theoretical distribution function. The question is whether this is justified if long-term estimates of future occurrences are important.

It follows that assumptions necessary in applying these probabilistic techniques must be defined. The first is that the data are strictly stationary in the statistical sense; for any subset t, no matter what the length of record (say $n > 25$), the probability distribution function, including all four moments, is identically the same. This says that the

mean, variance, skewness and kurtosis do not change with time. The second assumption is that the data are independent of each other or in other words the autocorrelation is zero.

As will be shown in the following discussion, most long-term climatically related data sets including hydrologic time series, are probably not strictly stationary and they are not independently distributed in time. Variance spectra of climatic data are presented showing why climatic time series of 30-50 years duration might appear to be nearly random (independent) in time, but when lengths of record in excess of 50 years are considered the data are not in fact random. The work of Hurst (1965) demonstrates that long-term annual runoff series are not random. Therefore, it appears obvious that in hydrologic analysis, for planning periods of 50 years or less (many engineering studies fall into this category), the traditional flow frequency analysis techniques may provide reasonable estimates of future flows. But even then there are problems, because as Wallis, Matalas and Slack (1977) point out, the distributions of the estimates of mean, standard deviation, and coefficient of skew are functions of n, the record length, the skewness of the distribution, and the probability distribution function itself. These results are from large sample analysis (100,000 and greater) based on Monte Carlo simulations and individual record lengths ranging from 10 to 90 years and a wide range of skewness for many different probability distributions.

To date, the use of the classic flow frequency analysis has been reasonably successful and thus accepted as a rational technique when complimented by an acceptable set of risk-related thresholds. In certain situations, however, such as adjudication of water rights, flood plain zoning and the like, longer term estimates are needed and it is not difficult to see that currently employed techniques may not be adequate.

The two primary objectives of this study are:

(1) to evaluate the sensitivity and responsiveness of currently employed hydrologic analysis and forecasting techniques to longer term changes in climatic state and variability and;

(2) to evaluate the known physical state of hydrologic processes in each of the 18 Water Resource Regions (for conterminous United States) as outlined by the Water Resource Council (WRC, 1978) and to <u>speculate</u> on the response of the system to superimposed climatic variability. Four climatic scenarios are evaluated encompassing all combinations of change in mean annual temperature of $\pm 2^{\circ}$ C and an accompanying change in total annual precipitation of $\pm 10\%$. The term <u>speculate</u> is stressed because no attempt is made to adequately model each region and numerically simulate the response with appropriate transfer function analysis techniques because neither time nor money is available to approach a project of such magnitude.

The science of climatology, along with many others, has a unique termi-

nology; because of this, it is necessary to define words that are used in this report. Most of these definitions are from The National Academy of Science publication, Understanding Climatic Change, (NAS, 1975).

Climatic state is the average of a complete set of atmospheric, hydrospheric and cryospheric variables over a specified period of time -- of considerable longer life span than individual synoptic weather systems -- in a specified domain of the earth-atmosphere system.

Climatic variation is the difference between climatic states of the same kind, for example, between two winters or two decades.

Climatic anomaly is the deviation of a particular climatic state from that expected based on a large sample of observations of the same time.

CLIMATIC CHANGE AND PATTERNS OF VARIATION

Although meteorological records in the conterminous United State are extremely short (temperature and precipitation records from the same station in excess of 70 years are rare), enough data exists to document the fact that climate has been variable. It is also apparent from these records that climatic variability is not a random function of time. Many authors (e.g. Julian, 1970) have shown that temporal variability in climatic records is not random in time but the tendency is towards "clustering" of groups of wet and dry years. Julian (1970) further indicates that there is a tendency for greater persistence in dry than in wet years when the two are compared spatially. Apparently the magnitude in variability of climate varies from place to place. For example, during the past five hundred years, the boundaries of the Alpine and sub-Alpine regions have experienced striking changes in glaciation (La Daurie, 1971) and considerable variations have occurred in the extent and the seasonal duration of sea ice (Lamb, 1977). Kraus (1958) shows that fluctuations of large amplitude occurred in rainfall and streamflow records from the sub-tropics, especially near the boundary with the arid zone. Lamb (1975) points out that an apparent shift in the world's rainfall pattern accompanied the vigorous general atmospheric circulation that prevailed during the early twentieth century warming period. Rainfall amounts increased generally in the zones of prevailing westerly winds in both hemispheres, from the west coasts far into the interior of the continents. Decreases in amount were noticed in the zones of the sub-tropical anticyclones (highs) but intensity of individual storms increased. This condition tended to spread toward latitude 40°-45° more southerly of the anticyclone belt. The monsoon rains penetrated northward into the southern fringe of the Sahara Desert and appeared to be more dependable than before in northern India.

Since the 1940's, the above tendencies seem to have reversed and the wind circulation patterns have become more meridional and smaller scale

systems have affected smaller scale moisture transport (Lamb, 1975). The northern polar ice cap regime has expanded along with a general displacement of major anticyclones and depressions toward the equator. Because of this, the equatorial rains have been restricted in their seasonal north-south migrations. As a result, lakes in equatorial Africa have risen while areas in latitudes 10°-20° N. and 12°-20° S. have experience repeated droughts or monsoon failures, often continuing over a number or years.

Dzerdzeevskii (1962) agrees that the twentieth century has experienced dramatic changes in atmospheric circulation with associated temperature and precipitation trends. However, he disagrees with Lamb as to the general circulation tendencies, suggesting the first half of the centure experienced atmospheric circulation that was more meridional than zonal (Figure 1).

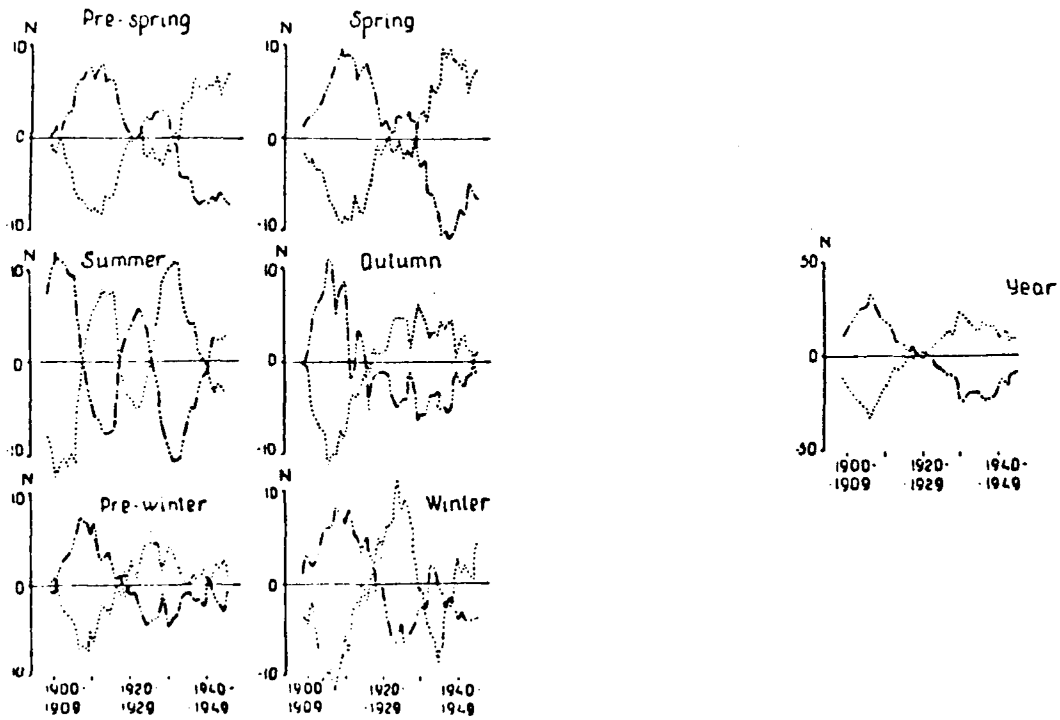


Figure 1. Departure of duration of zonal and meridional components of general circulation of the atmosphere over the Northern Hemisphere in the 20th century from long-period average values (a), seasons; (b) year. Where N equals duration (in days) of Dzerdzeevskii circulation types,···· the zonal circulation types dominant, -··- the meridional circulation types dominant, after Dzerdzeevskii (1962).

Although there is lack of agreement over the prevalent circulation type during the early 20th Century, it is apparent that there has been a significant variation in climate, at least in the mid-latitudes during the last 70-80 years. Kraus (1958) indicates that this variability has been restricted to the lower and mid-latitudes and relates the decrease in precipitation to reduced evaporation. He suggests that the reduction in evaporation may be related to ozone distribution and/or solar-weather relationships. Whatever the cause, the 20th Century has witnessed climatic variability and this in turn has been reflected in stream-runoff records. This climatic variability shows up in the record of the Nile at Aswan, the Colorado at Lee's Ferry, the Rio Grand and others, as a sustained high runoff period in the early 1900's followed by a decrease from 1920-1950. Kraus (1958) points out that this runoff pattern is typical throughout the lower and mid-latitudes of both southern and northern hemispheres. Karlan (University of Maine, 1977, personal communication) states that it is also characteristic of runoff records in Scandinavia. Based on runoff recrods for the conterminous United States, Hoyt and Langbein (1944) and Julian (1970) indicate that the wet first part of the twentieth century was typical for much of the country. Langbein (U.S. Geological Survey, 1978, personal communication), however indicated that the most noticeable effect is in runoff records of the southern intermountain area of the southwest, including the southern one-half of Nevada, Utah, and Colorado, all of Arizona and the western one-half of New Mexico.

Apparently climate is nowhere invariant. Kraus (1958) presents a technique for comparing trends in meteorolgical records where changes are illustrated by graphs of cumulative percent deviations from a mean. His graphs from the northern as well as the southern hemisphere show an increasing precipitation trend from 1881-1910 and decreasing from 1910-1950. These records include an average of total annual rainfall for Charleston, S.C., and Cape Hatteras, N.C., as well as the Nile River discharge at Aswan.

Van Loon and Williams (1976) suggest that regional trends in surface temperature are indeed connected with long wave circulation changes, that the greatest variations appear above 50° N. latitude, but that the changes may be compensated for in other regions. For example, during 1942-1972 there appears to have been a change of -1.4° C in the mean temperature above 60° N. latitude but this appears to have been offset by a +0.2° C change over the area between 30° N. to 30° S. latitude.

Budyko and Asakura (in NAS, 1975) show that for the period 1880-1969, average temperature for the northern hemisphere attained a maximum around 1940 and decreased until 1969. More recent records, however, indicate the decrease has leveled off and during the last 5 years and there has actually been little change. Budyko-Asakura's average temperature data for the northern hemisphere (Figure 2) shows the range of change between 1880 to 1940 to be approximately 1.1° C.

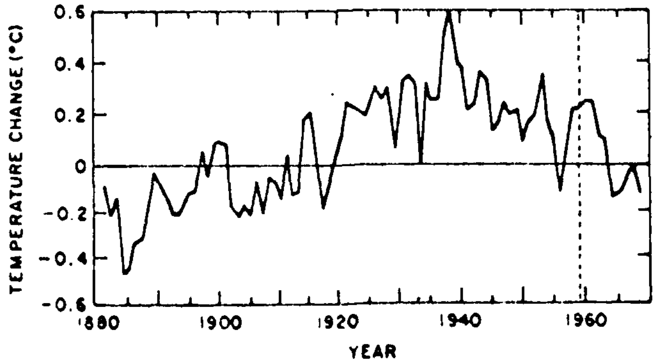


Figure 2. Recorded changes of annual mean temperature of the Northern Hemisphere as given by Budyko (1969) and as updated after 1959 by H. Asakura of the Japan Meteorological Agency (unpublished results). National Academy of Sciences 1975.

It is interesting to note that as late as 1977 (in guidelines for Determining Flood Flow Frequency, Bulletin No. 17A of the Hydrology Committee of the United States Water Resources Council) the following statement is made concerning the need for consideration of climatic variation in planning processes:

> "There is much speculation about climatic changes. Available evidence indicates that major changes occur in time scales involving thousands of years. In hydrologic analysis it is conventional to assume flood flows are not affected by climatic trends or cycles. Climatic time invariance was assumed when developing this guide."

There seems to be little agreement among climatologists concerning the most important cause of climatic variation. Possible causes include solar variability, oceanic changes and man himself, to name but a few. In fact, one of the greatest concerns among climatologists is the potential effect on climatic states by the CO_2 currently injected into the atmosphere by man-related activities. This fact alone should concern hydrologists if for no other reason than to be able to detect future changes in hydrologic processes.

The dominant atmospheric circulation features, whose variability leads to distinctive patterns of climatic variation, are the mean meridional circulation itself and the principal standing waves associated with the distribution of continents and oceans. The large land masses

in low and middle latitudes induce seasonal inflows and outflows, generally known as monsoonal circulations. These are most prevalent over India and southeast Asia. However, the seasonally associated rainfall in the southwestern and south-central United States is a similar occurrence which is relevant to the current discussion. At higher latitudes, the land-sea distribution and topography of the North American, European and Asian land masses leads to a pronounced standing multiple wave circulation pattern in the Northern Hemisphere. This wave pattern has been shown to vary from 3 to more than 10 waves with the greater number of waves leading to meridional circulation and fewer waves to zonal circulation (Figure 3).

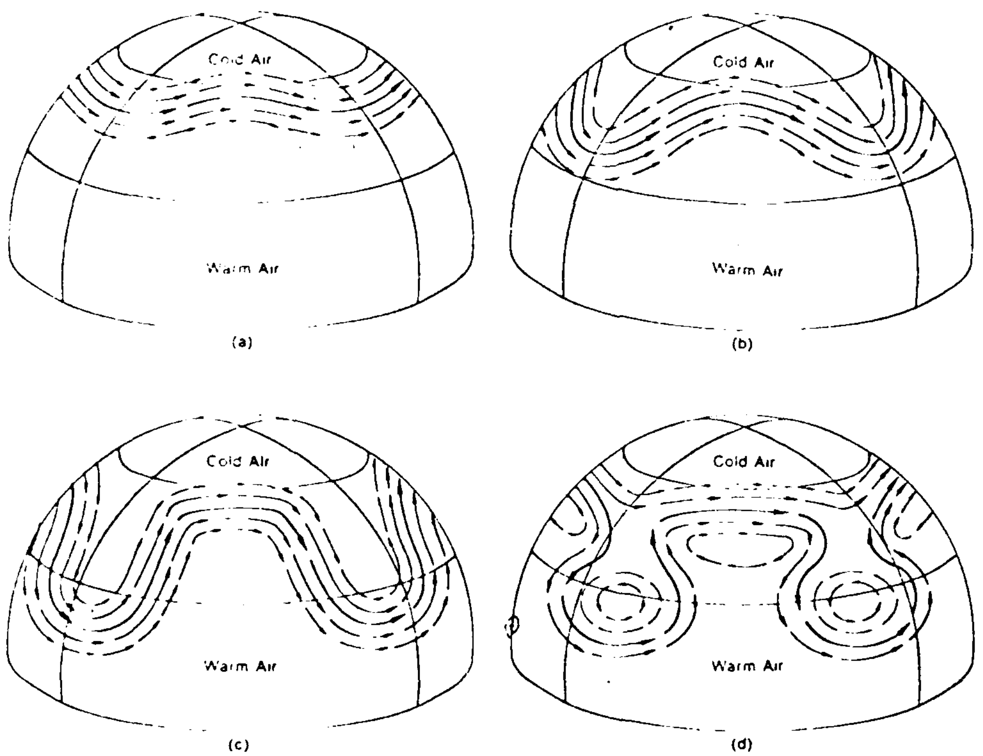


Figure 3. Variations in the circumpolar vortex (after Muller, 1974, p. 122)

An idealized diagram of the mean flow is shown in (a). In this scheme, the circumpolar westerly waves in the atmosphere tend to balance the energy deficit of the polar latitudes and the energy surplus of the lower latitudes by broadscale movements of warm and cold air masses in a poleward or equatorward direction. However, an even greater exchange of energy occurs when there is an equatorward expansion of these westerly winds,

causing a greater number and higher amplitude waves to develop in a more meridional circulation component (Figure 3b, c). Hence these types of circulations are important in times of hemispheric-wide energy deficits (colder temperatures) in the non-tropical latitudes. When the temperature deficit between high and low latitudes is not as great (i.e. warmer seasons or warmer climatic periods) a more zonal type of circulation evolves as in Figure 3a and is characterized by a contraction of the circumpolar vortex and low amplitude standing waves. Changes in the wave regime of the general circulation, (Figure 3; a,b,c,d) can occur rapidly (e.g. over a period of 4-6 weeks) with intensity also variable. It is the persistence of either zonal or meridional types of circulation over a given time period which characterizes the climate of a particular season, year, decade, century or millenium.

Although the general hemispheric circulation can be used to typify large scale climate and climatic variations, local and regional variations can and do result from the larger scale features. Figure 4 (a,b,c) shows some of the possible variations in an east-west direction over the United States resulting from large amplitude meridional atmospheric circulation. Figure 4a depicts a meridional circulation with a strong ridge (upper air high pressure) and associated warm surface air positioned over the western United States. Conversely, a strong low pressure trough lies over the eastern two-thirds of the country and colder than normal surface temperatures occur. Such a situation could occur with hemispherical circulation similar to that shown in Figure 3c. If such a pattern persisted, temperatures in the west would tend to be warmer while those in the east would be cooler than average. Precipitation could be above average in the west if the warm air mass associated with the ridge had a predominantly marine origin. Precipitation in the east might be below average if the dominance of the cold air was dry and arctic in origin.

Consider further the same type of circulation, persistence, and intensity but with the position of the standing waves displaced westward so that a trough of upper air low pressure is situated over the western United States and a ridge of upper air high pressure dominates the east (Figure 4b). The regional climatic response would be the inverse of that shown in Figure 4a. Figure 4c illustrates a third case in which a zonal type of circulation pattern is dominant. In this case, similar temperature conditions might result across the United States in an east-west direction, but the precipitation response could be quite different. Strong westerly winds off the Pacific Ocean would steer moist air masses over the western part of the continent, but by the time they penetrated to the midwest, most of the moisture would probably have been lost in western mountain ranges and the nature of the air masses would change from wet to mild and dry.

Several studies have tended to verify this example. For example, Wahl (1968) and Wahl and Lawson (1970) show that temperature departures from the 1931-60 "norm" were negative in the eastern and positive in the western United States for the mid-1800's and the 1960's. The circulation from 1931 to 1960 tended to be zonal whereas that of the mid-1800's and 1960's appears to have been more meridional, explaining the contrasting

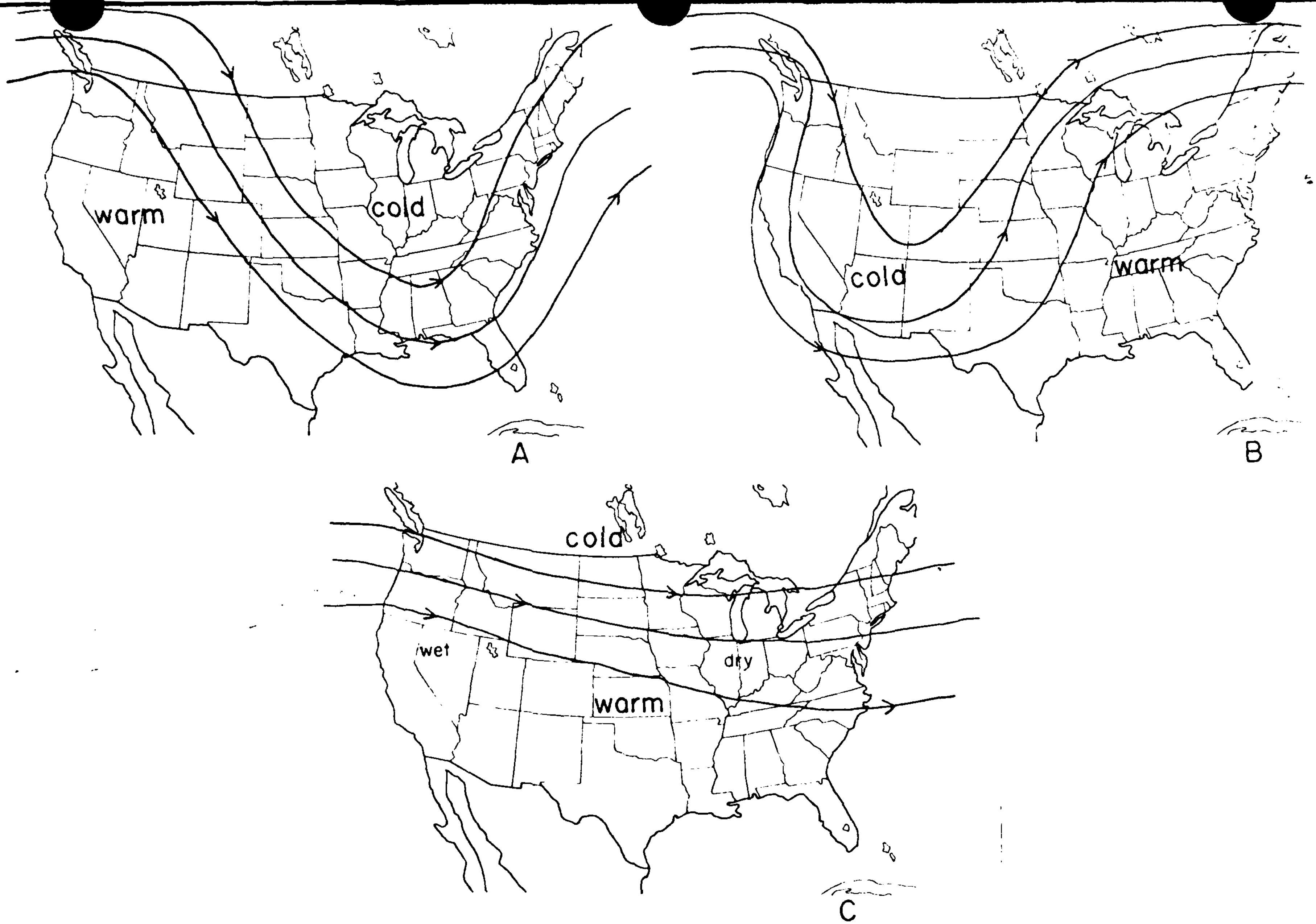


Figure 4. Local climatic response to broadscale circulation patterns after Hirschboeck, 1976, (unpublished paper, Dept. of Geosciences, Univ. of Arizona).

temperature anomalies. Mitchell (1961) indicated that it is not unreasonable to expect secular temperature changes to vary as much with longitude as they do with latitude. Fritts and Lofgren (1978) show that the winters of 1976-77 and 1977-78 were the result of a circulation regime similar to that depicted in Figure 4a. Furthermore they conclude that "there is a reasonable likelihood that winters like the last two extreme ones could occur considerably more frequently than observed by the (20th Century) observational record."

This point is also well made by Bryson and Hare (1974) who state that the atmospheric circulation has distinctive monthly patterns which interact with surface thermal and topographic characteristics to give each place on earth a particular annual sequence of dominant airstreams. These airstreams, with physical properties derived from their previous history, plus the dynamics of the locale and its radiation regime, largely determine the climatic character of a given region. This results in an annual sequence of meteorological parameter assemblages which characterize regions based upon the preferred location of the airstream boundaries. The seasonal locations of airstream boundaries over North America are shown in Figure 5. It is not difficult to associate these airstream boundaries with the monthly distribution of streamflow in Figure 6.

One objective of this study is to identify those regions in the United States most likely to be affected by future climatic variability. One approach is to assess the frequency of changes in origin of air masses in such regions. Those most susceptible to variation would likely be the marginal regions of air mass dominance. In essence the air masses overlying the United States are those originating in the Arctic, the North Pacific or the Gulf of Mexico. The number of months that certain areas of North America are dominated by arctic air is shown in Figure 7 and indicates that the upper north-central and eastern portions of the United States are dominated by these air masses roughly 4 months of the year. Presumably, this would represent the winter months. Consequently, this region would be quite susceptible to atmospheric circulation variability resulting in changes in winter climate. The result might be colder winter temperatures (or warmer) depending on the direction of change in position of the air mass dominance. In contrast, the number of months that areas of the the North American continent is dominated by air masses of Pacific Ocean origin is shown by Figure 8. Based on this diagram the greatest probability of change might be expected in the boundary areas in the south-central Great Plains and northeastern United States. The southeastern U.S. is dominated by Gulf of Mexico air most of the time. Based on this analysis, the regions of least susceptibility to climatic variation would be the extreme Northwest and the southeastern portion of the United States. Regions of greatest susceptibility to climatic variability are the Rocky Mountain region, northeastward along the Great Plains to the northeastern tip of the United States.

The relatively short period that meteorological and hydrological records have been instrumented necessitates the use of secondary (proxy) data in investigating climatic variability for periods greater than the

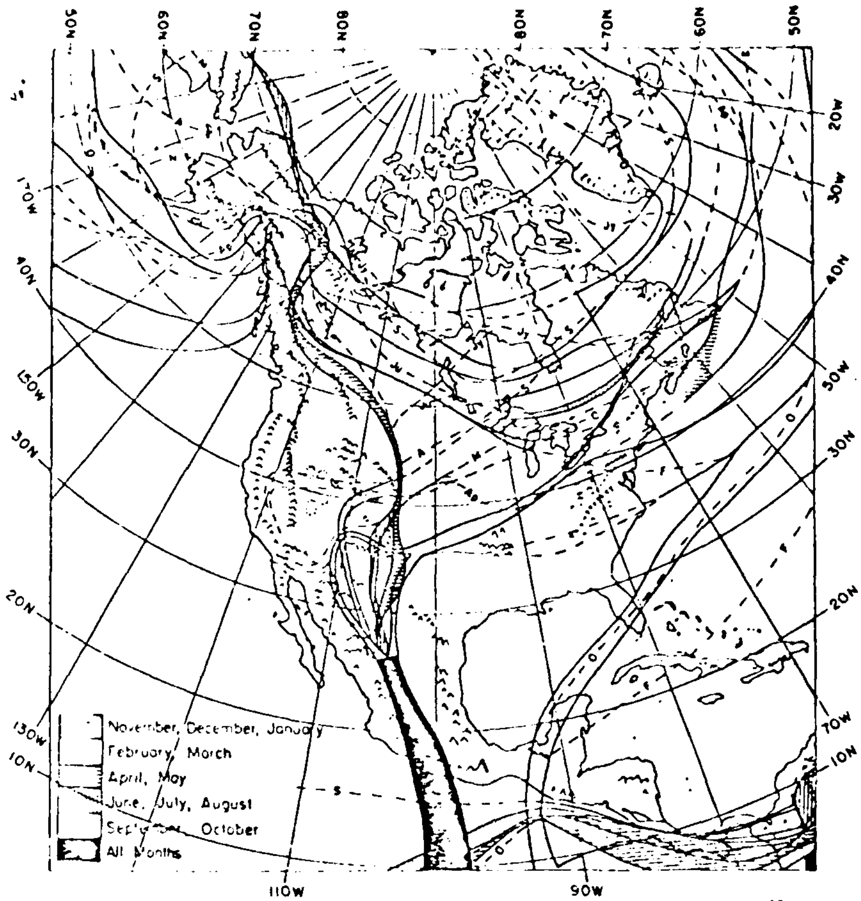


Figure 5. Locations of air stream boundaries in the North American region. Shaded areas indicate zones in which the boundaries lie very close to the same position during a climatic season or more. The dashed boundaries shown in the western United States are from Mitchell, 1969. After Bryson and Hare, 1974.

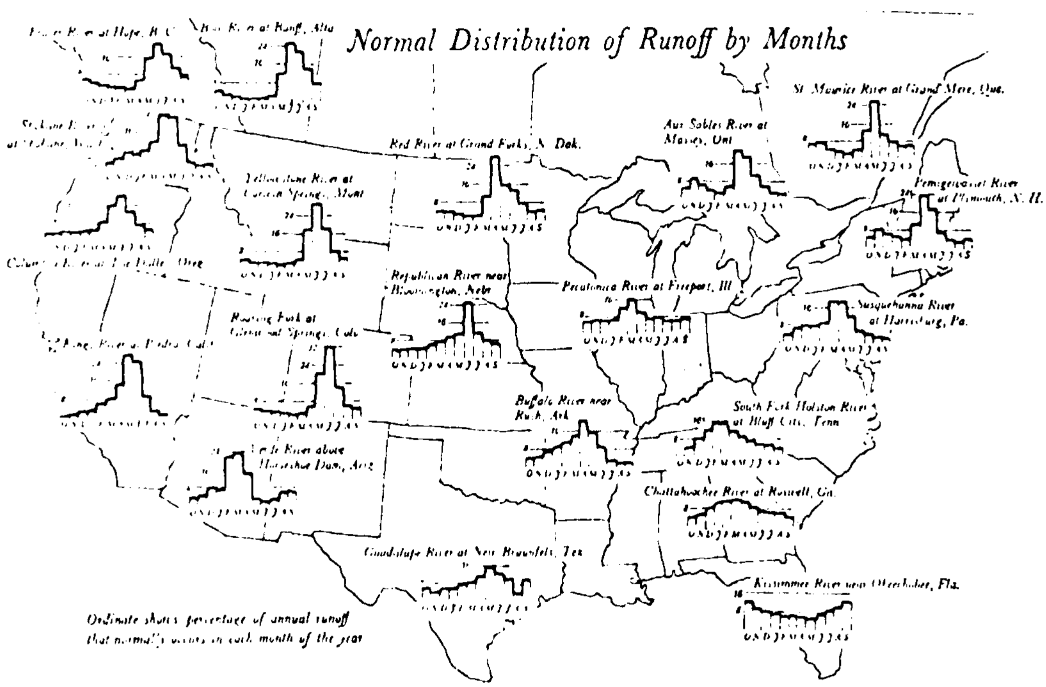


Figure 6. Distribution of monthly runoff in the United States (Langbein and Wells).

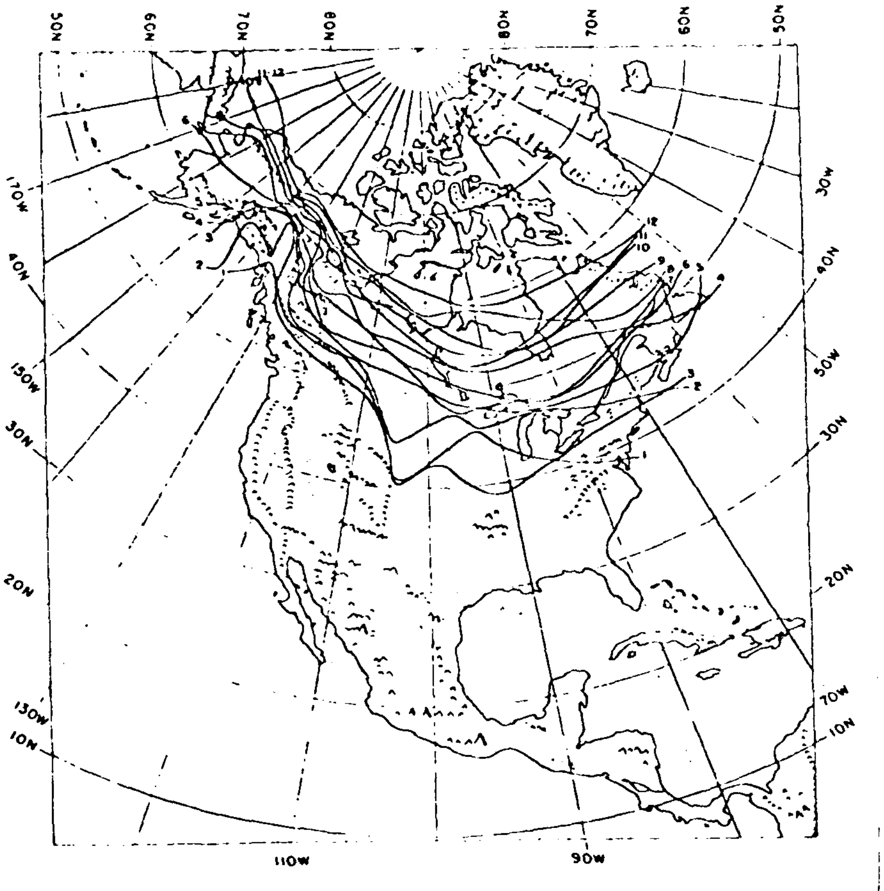


Figure 7. Duration of dominance of Artic airstream in months. From Bryson and Hare, 1974.

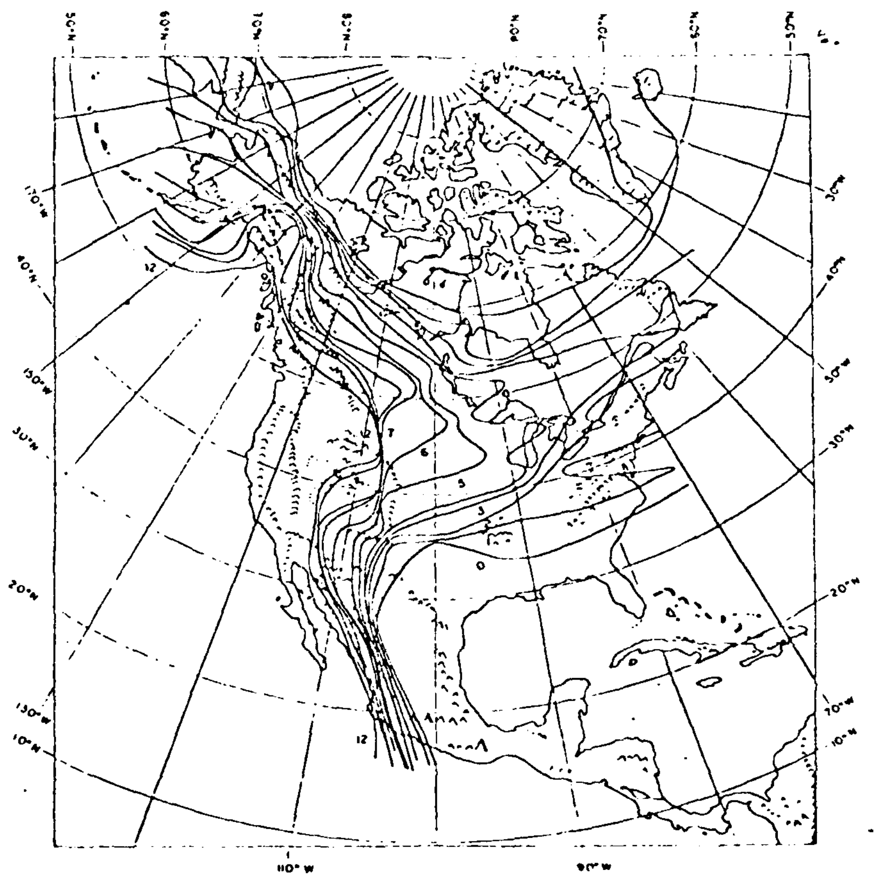


Figure 8. Duration of dominance of the Pacific airstream in months. From Bryson and Hare, 1974.

100-year recurrence range. Several informative articles have been published documenting the kinds of indicators that can be used (e.g., NAS, 1975; Stockton, in NAS, 1977). However, little has been written about the precautions that must be exercised in the use of these techniques. Every proxy record used today acts as a filter in the information contained and they should not be interpreted as being superior to instrumented measurements. Suffice it to say that if 500 years of climatic records are required and a record of that length has been continuously gaged at a nearby station, then that record should be used, not one interpreted from some proxy source. The 500-year-period is referenced because it has been documented that this length of time is needed to obtain reliable estimates of the low frequency (long-term climatic) signal inherent in hydrologic records of surface runoff (J.R. Wallis, Watson Research Center, I.B.M., 1977, personal communication). Unfortunately, records in the 500-year range do not exist in most parts of the world and some kind of proxy record must be used to obtain needed estimates of the climatic signal, preferably verified with proxy records of a different nature.

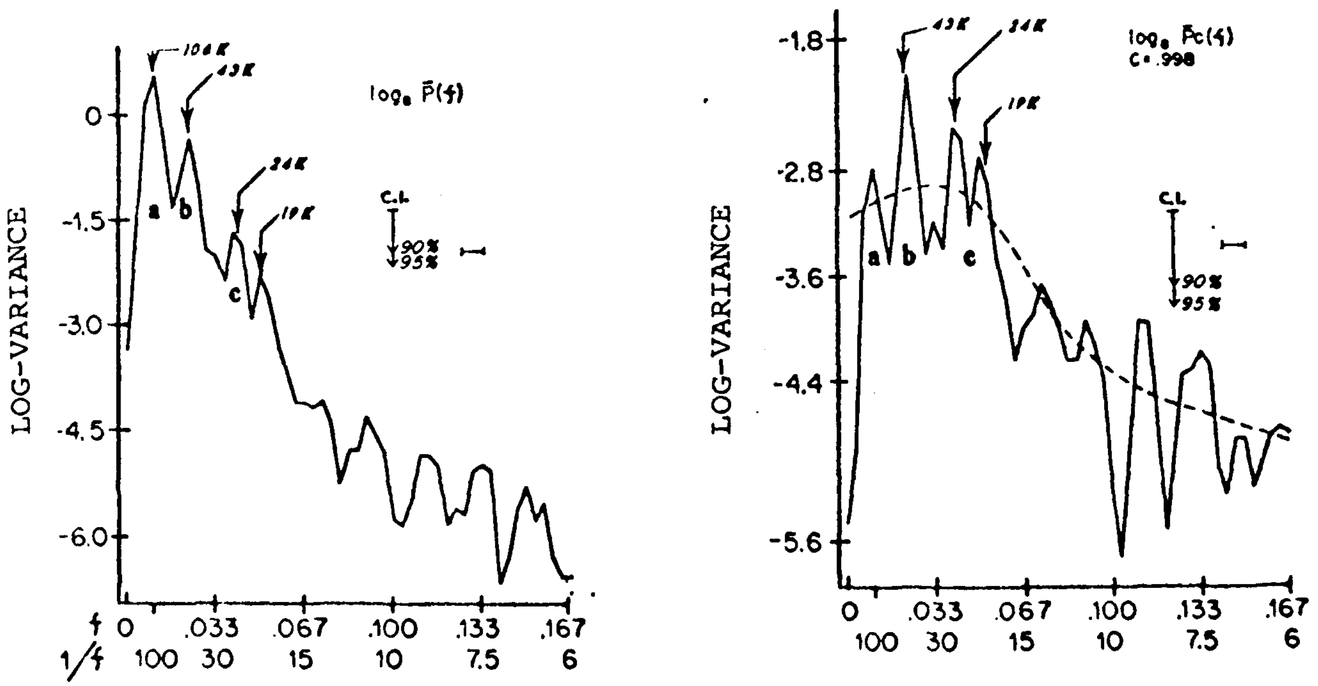
Layered ice cores, layered lake, swamp or bog sediments (pollen), and tree-rings are the most widely used sources to provide continuous time series estimates of climatic variation in the 10 to 10^3 year range. Proxy indicators, however, possess differing degrees of resolution. For instance, ice cores and pollen analysis can be used to estimate paleoclimatic parameters but the uncertainty in dating makes them undesirable when high frequency (short-term climatic) information is desired. In contrast, tree-ring data can be precisely dated and the climatic signal is inherent in the ring widths. Thus the lack of resolution in most proxy data sources drastically limits their use in climatic reconstructions in the 10 to 10^3 year range. These limitations in the use of such sources have been documented by Stockton (1977).

In hydrology and water resource management, the planning horizon of concern is approximately 50 to 100 years in the future. In most planning processes, the assumption is made that the system under study is strictly stationary in the statistical sense, and consequently a theoretical probability distribution can be assumed and probability estimates of future occurrences made. The assumption of stationarity is not bad when planning horizons for 10 to 20 years are involved because of the slow response time of the atmosphere to different forcing functions. But for periods greater than 30 years, this assumption can lead to serious consequences especially under the current planning restrictions which require multiple uses of water both instream and offstream so that the margin for safety is quite restricted.

According to Hasselman (1976) the foremost problem facing climatologists is to determine the distribution of frequency of climatic variations over the entire time range of intervals from 10^{-1} to 10^6 years. Although a seemingly impossible task, it is surprising how much is already known, especially about the time span 10^4 to 10^6 years when investigators from different fields met recently to assess the present state of knowledge.

It is equally surprising how little is known for the 10 to 10^3 time span.

Spectral analysis is one statistical technique that is commonly used to analyze the distribution of variance with frequency. Figure 9 shows autospectral functions of oxygen isotope series derived from a deep sea core from the southern Indian Ocean (Hays et al., 1976); the isotope series is interpreted to reflect the waxing and waning of continental ice sheets.



FREQUENCY IN CYCLES/1000 YEARS

Figure 9. Climatic spectra representing variations in the total volume of global ice over the past 468,000 years, as recorded in the oxygen-isotope records of a deep-sea core from the Southern Indian Ocean (Hays et al., 1976). N = 157, time increment = 3,000 years. A-B; Spectra estimated by autocovariance methods. B is prewhitened.

The spectra are computed by the direct method as described by Blackman and Tukey (1958) and Jenkins and Watts (1968). The important aspects of these functions are that the variance tends to increase to about 100,000 years and then decreases thereafter. The slope of the increase is equal to -2

(when plotted on a log-log scale -- not shown) which seems to indicate the rate of increase in variance with time. Note also the tendency for peaks at 43,000, 24,000, and 19,000 years. These are interpreted changes in climate resulting from variations in the earth's solar orbit. Changes in climate on this time scale are of only limited interest to hydrologists (except in the selection of disposal sites of radioactive wastes possessing extremely long half-lives) but does serve to indicate that variance in climate does not increase to infinity and that the increase might be of the order of log variance = -2 log time.

In the time range of 10^0 to 10^4 years, Kutzbach and Bryson (1975) have published an autospectral function of winter temperature as interpreted from different records. As shown, (Figure 10), frequency is plotted on a logarithmic scale to accomodate the broad frequency range. The ordinate is plotted as variance spectral density V(f) times frequency (f) such that equal areas under the curve represent equal variance. (In this coordinate system, a white noise spectrum slopes upward with increasing frequency.) Using this as a guide Figure 10 reveals a high percentage of the variance concentrated in the range 1 to 50 years, with another large portion being in the 1000 to 10,000 year range. Little variance appears to be concentrated in the 50 to 1000 year range but this is partly due to the way the data are plotted and partly because of the lack of information concerning climatic variation in this time horizon. The data are plotted more conventionally in Figure 11 as percent variation versus frequency. Here it is more apparent that the deviation from the white noise spectrum occurs somewhere between 50 to 100 years.

As the authors point out, the historical records may represent a slight underestimation of the lower frequency while the O_{18} ice core data may be an over estimation because of problems with high frequency resolution. If one assumes the instrumented record to be "correct", at least for winter temperature, the departure from the white noise spectrum occurs at approximately 30 years. This indicates that seasonal and perhaps annual temperature records of less than 30 years in duration would be expected to conform to the properties of a white noise process. Thus, to investigate the "true spectrum", a much longer record is necessary. The essential point is that there is clear evidence that climate can and does vary on all time scales and as Hasselman (1976) has distinctly put it, "An understanding of the origin of climate variability, in the entire spectral range from extreme ice age changes to seasonal anomalies, is a primary goal of climate research." This statement may be aptly paraphrased as "an understanding of the possible influence of climatic variation -- on all hydrologic processes -- in the entire spectral range from extreme ice age to seasonal anomalies, is a primary goal of hydrologic research."

An attempt has been made to understand the relationship between relative rate of climatic change and period of fluctuation (NAS, 1975). The curves shown in Figure 12 represent a log-log plot of rate of climatic change versus period of fluctuation based on data from sea cores, ice cores and upon the work of Kutzbach and Bryson (1975). In addition, applicable lines for different values of first order autocorrelation functions (r-value)

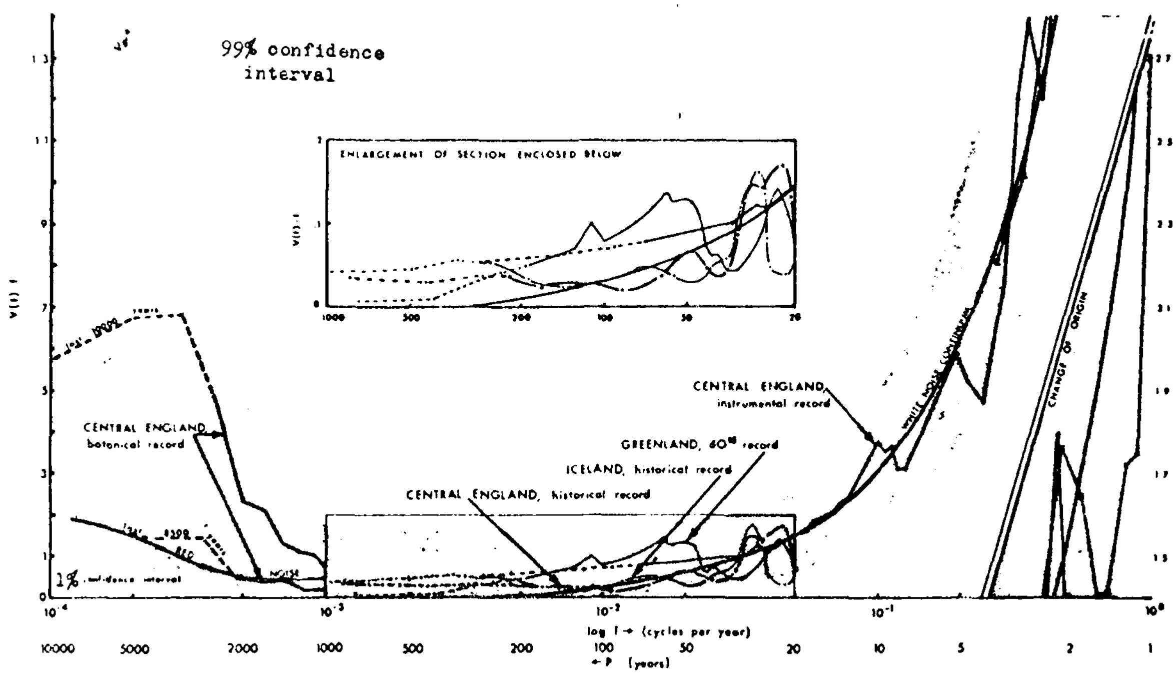


Figure 10. Composite variance spectrum of temperature on time scales of 10^0 - 10^4 years derived from instrumental, historical δO^{18} and botanical records. The ordinate is V(f) times f[units, ($^oC)^2$], the abscissa a logarithmic frequency scale. The four lowest frequency spectral estimates of each individual spectrum are connected by dashed lines to indicate that they are unreliable in a statistical sense. Stippling indicates a generalized version of 1 and 99% confidence limits. The insert in the middle figure ia an enlarged version of the intermediate frequency section. Greenland spectral estimates have been halved. After Kutzbach and Bryson (1974).

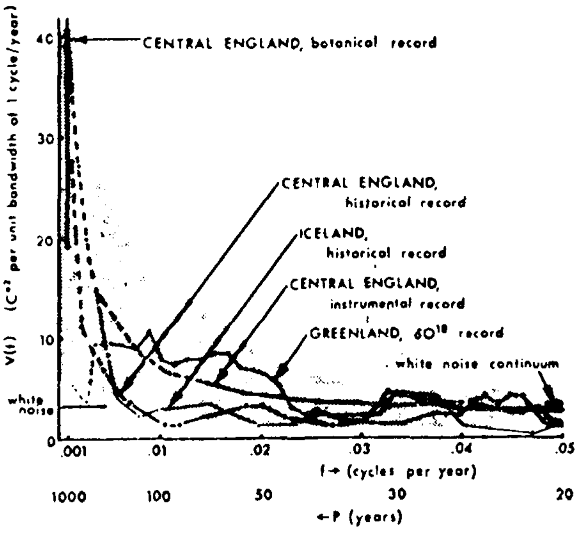


Figure 11. Composite variance spectrum of temperature on time scales of 10^1 to 10^3 years derived from instrumental, historical, δO^{18} and botanical records. Ordinate is V(f)[($^oC)^2$ per unit frequency bandwidth of 1 cycle per year] and abscissa a linear frequency scale. After Kutzbach and Bryson (1974).

are shown, assuming a first order autoregressive generating mechanism. The diagram illustrates at least two points: 1) the periodic tendencies documented by the autospectral functions represent a relatively small portion of the relative change; and 2) the assumption of a first order autoregressive function does not fit the data well, especially in the larger period of fluctuation -- lower relative rate of change region of the graph. The most appropriate r-value in the higher frequency range is relatively low (r = .20) indicating a relatively small memory in the climatic process.

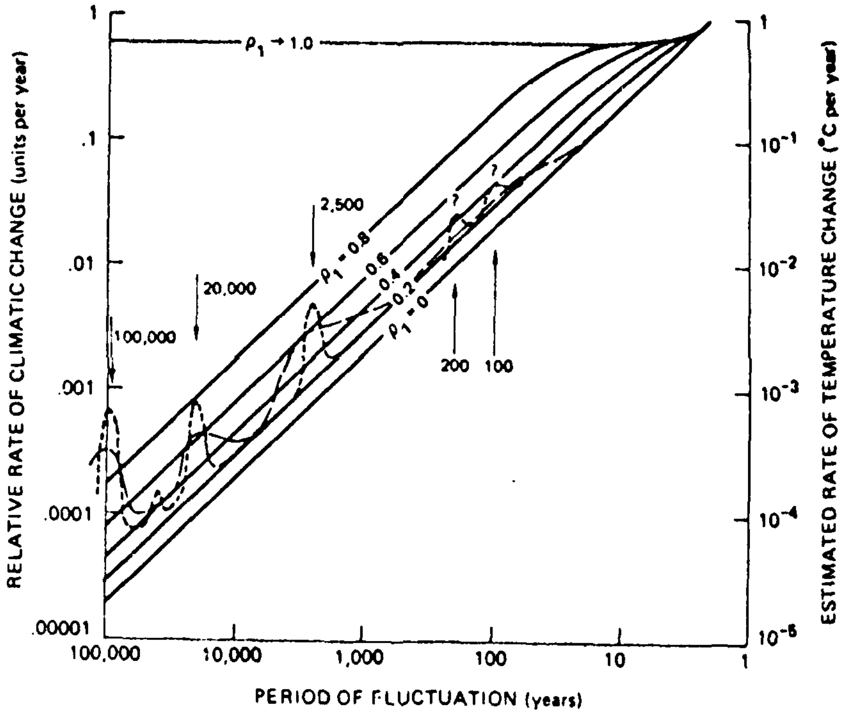


Figure 12. Relative (maximum) rate of change of climate contributed by climatic fluctuations, as a function of characteristic wavelength. The family of parallel curves shows the expected relationship in Markovian "red noise" as characterized by the serial correlation coefficient at a lag of one year. The dashed line is a conservative estimate of actual climate as inferred from proxy data. The dotted curve shows the modifications to be expected if the principal fluctuaions were actually quasi-periodic. After NAS (1975).

CLIMATIC VARIATION AND HYDROLOGIC RESPONSE

An early serious attempt to quantify the relationship between climate and streamflow in the United States was by Hoyt and Langbein in 1944, who pointed out some of the details of the climate-runoff relationships. They published a series of year-by-year maps for water years 1910-11 through 1941-42 showing spatial and temporal changes in annual runoff for 6 regions of the United States. The authors point out the tendency for greatest persistence in both time and space for dry years as opposed to wet years. This same conclusion was reached by Julian (1970) who utilized a different approach. Hoyt and Langbein (1944) also conducted a detailed investigation of the relationships between monthly mean temperature, total monthly precipitation and monthly runoff for the Sacandaga River, near Hope, New York. Later, Langbein et al. (1949) published a more general version of curves showing the relationship developed in the 1944 study.

At about the same time Hoyt and Langbein were working in the United States, H.E. Hurst, a hydraulic engineer working on reservoir design for the Nile River and essentially isolated from other hydrologists, was carrying out pioneering work in defining and quantifying climatic persistence in hydrologic records. As Mandelbrot (1977) notes:

> "It is precisely the fact that Hurst was working so far from any major center of learning that explains the birth of his idea and its survival. Had Hurst sought sound statistical advice, one may well fear he would have been directed toward some technique claiming universal applicability, for example toward the most dificult of all spectral analysis."

Based on his Nile River studies and experience, Hurst demonstrated that:

$$R/S = \left(\frac{n}{2}\right)^k$$

where R = range of cumulative departures from the mean of a time series.

S = standard deviation of the series.

n = length of record in years.

k = coefficient which varies from 0.5 for a purely random process to > 0.5 (average of 0.72) for all climatically related processes such as annual river runoff series, tree-ring width series.

Theory indicates that k = 0.5 in all cases. When Hurst first made his claim that k was in fact > 0.5, many theoreticians set out to prove him

wrong. But Hurst was adamant in his conviction that $k > 0.5$, and significant, although the ratio R/S was unknown to statisticians and not subject to rigorous significance tests. Hurst's point prevailed through time and according to Mandelbrot (1977), E.H. Lloyd, the British mathematician finally said of Hurst's findings:

> "We are, then, in one of those situations so salutary for theoreticians, in which empirical discoveries stubbornly refuse to accord with theory. All the researches described above lead to the conclusion that in the long run R/S should increase like $n^{0.5}$, whereas Hurst's extraordinarily well-documented empirical law shows an increase like n^k where k is about 0.7. We are forced to the conclusion that either the theorists' interpretation of their work is inadequate or their theories are falsely based. Possibly both conclusions apply."

Hurst's findings are of prime importance to the hydrologist and those involved in reservoir design for it provides evidence of long-term persistence in flow records and a quantitative measure of it. Of prime importance in reservoir design is its size such that a series of curves can be established relating yield with capacity. These curves are especially sensitive to persistence in the reservoir inflow series, that is the tendency for a series of low flow (or high flow) series to be grouped together. This is the tendency of a time series that the Hurst coefficient attempts to quantify. Knowing regional values of k and using models that incorporate it as a parameter, allows reservoir operation studies of the Hurst effect. If important and economically worthwhile, the design can be appropriately modified.

It now seems apparent that Hurst's work demonstrated the fact that $k > 0.5$ because of the climatically induced low frequency signal in the records he analyzed and furthermore that climate is not a random function of time. Climatologists probably knew this long before Hurst's classic experiments but it was this "intriguing" find that opened the eyes of the hydrologic world (although it was not immediate). It took the later work of Mandelbrot and Wallis (1968) to provide the stimulus. Hurst's work was also significant to the hydrologists because he demonstrated that his findings had major ramifications on the size and operations of reservoirs.

There has been much conjecture concerning the cause of the $k > 0.5$ finding. Although Hurst explicitly indicated that he felt it to be climatically induced, many thought some other cause was predominant. Hurst readily admitted his results were based on Gaussian distributed variables. Some thought that when other distributions were considered, the law would break down. Since then, Rosenblatt, (University of California at La Jolla, 1978, personal communication), has indicated that the relationship holds for a wide range of third order processes. Apparently skewness of the probability distribution is not a critical factor in the value of k.

Mandlebrot and Wallis (1968, 1969a, 1969) in a series of papers documented the existence of the Hurst phenomenon and proposed a general class of mathematical models called "fractional gaussian noises" (fgn) to duplicate the statistical properties of a process exhibiting the Hurst phenomenon. Mandelbrot (1977) in a recently published book called "Fractals" describes the universality of the fgn process. He has coined the term "Joseph Effect" to designate all phenomena characterized by long-term persistence. This introduces the concept of "infinite variance", Granger and Orr (1972), in which the probability distribution function of a series (time series) has "stretched tails" such that the tails of the distribution function continue to infinity instead of approaching some finite value. Many workers find the concept of "infinite memory" to be unappealing because there appear to be examples of "step function" like changes in past climate (see for example NAS, 1975, p. 31, La Marche, 1973). Klemes (1974) finding the concept of "infinite memory" incompatible with his belief of physical reality, suggested the Hurst phenomenon to be the result of nonstationarity in the mean (a result of climatic variation). Potter (1976) analyzing individual precipitation records in eastern United States, arrives at the same conclusion that nonstationarity (in climate), not infinite memory is the basic cause of the Hurst phenomenon. Granger and Orr (1972) point out in their tests for "infinite variance" that nonstationarity and autocorrelation affect their converging variance tests for infinite variance. Mandelbrot (1977) claims that nonstationarity is not a valid explanation and proposes there is no proof in claiming "these are anything but the most convenient after-the-fact labels for seven, seventeen, or seventy-year-long periods of dry or wet weather" (p. 248).

Julian (1970) in an extension of the work Hoyt and Langbein (1944), analyzed a selected spatial network of streamflow stations and precipitation stations for their space and time variation characteristics. The rank-order statistic methodology used by Julian is desirable because 1) it is nonparametric permitting anlysis of data from different unknown probability distribution formations; and 2) it allows assessment of the extent of comparable variation in the spatial and temporal associations in the data. The results confirm and quantify those found earlier by Hoyt and Langbein. The results show a tendency for lack of comparable variations in the spatial coherence of streamflow data with the drier years (lower streamflow) showing a greater spatial coherence than wetter years (high streamflow). Physically, this result can be interpreted to mean that drought has a greater spatial correlation than non-drought. Julian also shows a map of average difference in the spatial correlation coefficients of the dry minus the wet years. This map (Figure 13) shows that dry years do not exhibit a higher coherence on a larger horizontal scale, but rather are more homogeneous toward the internal portions of the continent. This is seen as quantification of the earlier statement that the northwest and southeast portions of the Nation were seen as regions least likely to experience climatic variation.

Julian (1970) also investigated the temporal coherence of the streamflow and precipitation networks. Using a runs test, he concluded that there is a tendency for greater coherence during dry years (low runoff)

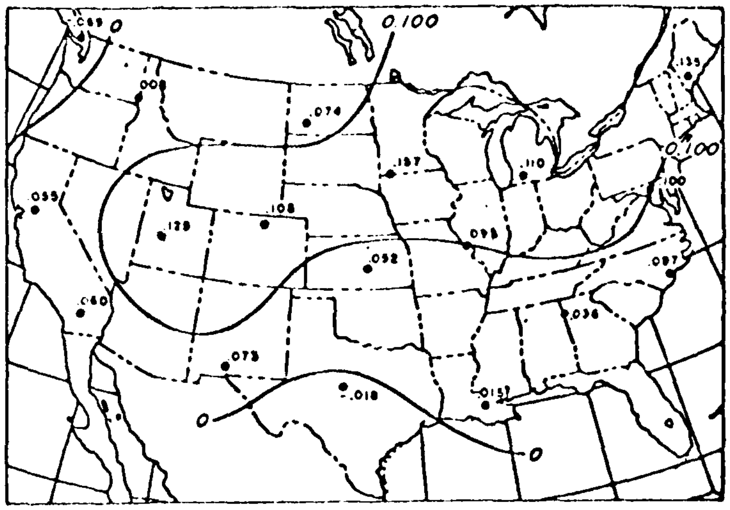


Figure 13. Map of the average differences in correlation (as expressed by correlation coefficients) of dry years over wet years between precipitation stations indicated by the dots and for the period November - May. The map shows that the stations in the interior and the northeast regions of the country are better intercorrelated in dry periods than in wet ones. After Julian (1970).

than for wet years (high runoff). The same appears true for at least one precipitation network for the monthly combination of November through May. The conclusion reached is that there is a stronger relationship between streamflow and precipitation in dry than in wet years -- a result that is expected since total annual runoff is roughly equal to total precipitation minus total evapotranspiration (on a water year basis). Consequently, in dry periods, a much larger portion of the precipitation is used to satisfy evapotranspiration demands and a smaller runoff occurs.

Julian makes another point that is worth noting. When the dispersion of numbers of wet and dry years occurring before and after 1923 was determined from both streamflow and precipitation networks, there was a strong bias toward wet years occurring prior to 1923 and for dry years occurring after. This is consistent with Stockton and Jacoby's (1976) findings for the Colorado River and what others have noted about climatic indicators such as movement of Alpine glaciers throughout the world.

Recently, under the auspices of the National Science Foundation, our group at the University of Arizona Laboratory of Tree-Ring Research has been studying the long-term spatial and temporal behavior of drought in the western two-thirds of the Nation. The primary purpose of the study is to establish the long-term history of large-scale drought; whether the long-term recurrence shows any periodic tendencies; and what areas, if any,

show the greatest likelihood of drought. The Palmer Drought Severity Index (PDSI) as defined by Palmer (1965) is used as a measure of drought severity-duration. A grid of tree-ring data series comprised of from 40 to 65 mean value functions, each of which is the average of at least 20 samples, is used to extend the record back to the year 1600.

The Palmer Drought Severity Index (PDSI) is based on an empirical water balance approach and provides a scaled index of drought conditions in different climatic regions. The Thornthwaite method (Thornthwaite, 1948, Thornthwaite and Mather, 1955) of computing potential evapotranspiration from readily available precipitation and temperature data forms a basis for calculating the climatic demand for moisture and the subsequent development of the PDSI. The PDSI for a given month is determined partly by the value of the Index for the preceding month through an autoregressive relationship and partly from moisture received during the month in question. A moisture anomaly is defined as the departure of the actual precipitation received from that expected under "normal" moisture conditions. The "expected" precipitation is calculated by the water balance approach and takes into account accumulated soil moisture levels and estimated evapotranspiration.

The PDSI scale is shown in Table 1.

TABLE 1

DROUGHT CLASSIFICATION BY PALMER DROUGHT SEVERITY INDEX (PDSI)

Palmer index	Degree of drought
PDSI $\leq$ -4.0	Extremely dry
-4.0 < " $\leq$ -3.0	Severely dry
-3.0 < " $\leq$ -2.0	Moderately dry
-2.0 < " $\leq$ -1.0	Mildly dry
-1.0 < " < +1.0	Near normal
+1.0 $\leq$ " < +2.0	Mildly wet
+2.0 $\leq$ " < +3.0	Moderately wet
+3.0 $\leq$ " < +4.0	Severely wet
+4.0 $\leq$ "	Extremely wet

The PDSI, for which maps are published by the National Oceanic and Atmospheric Administration in the Weekly Weather and Crop Bulletin, has the desirable property that a given PDSI value means roughly the same degree of drought from one location to another. Also, the PDSI is an integrative index of moisture conditions similar to the response recorded in tree-ring width series. From a hydrologic standpoint, the PDSI is a desirable index for slower response systems such as fluctuation

in ground water levels and water storage in large reservoirs.

Three basic tree-ring data grids have been used to reconstruct the PDSI for 40 climatic regions in the western two-thirds of the Nation. The spatial distribution of the tree-ring grids and the location of the 40 climatic regions are shown in Figure 14.

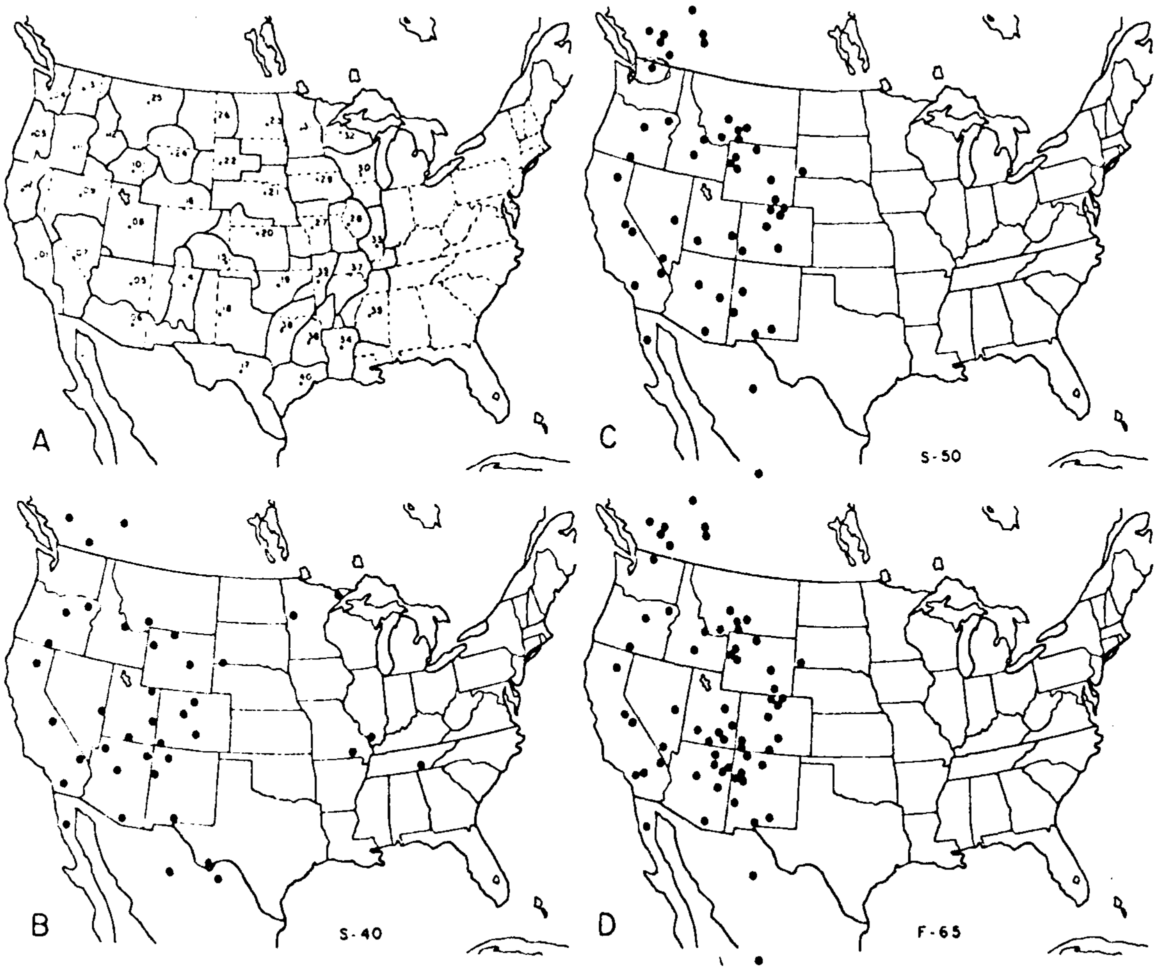


Figure 14. Domain of drought analysis on which this study is based. 1(A): Areas with solid boundaries and interior numbers indentify the 40 climatic regions in which Palmer Drought Severity Index was observed or reconstructed. 1(B): Spatial distribution of tree-ring data sites designated as S-40, used in reconstructing PDSI to 1700 A.D. 1(C): Spatial distribution of tree-ring sites designated as S-50, used in reconstructing PDSI to 1601 A.D. 1(D): Spatial distribution of tree-ring sites designated as F-65, used in reconstructing PDSI to 1600 A.D.

Using meteorological data collected for the period 1931-1962, a multivariate transfer function was derived between the PDSI computed from the gaged temperature and precipitation data for July and the tree-ring data from each of the three tree-ring grids S-40, S-50, F-65. The derived transfer function was then used to reconstruct the July PDSI for the period 1700-1962 from grid S-40 and 1600-1962 from grids S-50 and F-65 for each of the 40 climatic regions. July maps of PDSI were then developed for each year in the area covered by the 40 climatic regions.

Since drought was to be reconstructed from annual tree-ring indices, while the regional PDSI series consisted to monthly values, it was necessary to derived some annual measure of drought from the PDSI series that would yield a strong relationship to tree growth. The July PDSI was chosen for the following reasons: annual tree growth as reflected in the ring widths is usually nearly complete by the end of July; July PDSI reflects, to some degree, the moisture conditions of the prior spring and late winter and these conditions are relatively important to most of the species of trees used in this study; major droughts from 1931-1970 tended to peak in intensity during July or August; and July PDSI is particularly important in the growth and yield of agricultural crops. At least two results of this research are of interest in this study.

If relative drought area is plotted, as defined by the 40 climatic regions, as a function of time (Figure 15), the resulting waxing and waning of drought area possess a rhythm with a near 22-year period. This means that approximately every 22 years, the total area of western United States involved in drought will tend to increase. The last major drought occurred during 1974-76, the one before that in 1954-56, and that was preceded by the great drought of 1934-36.

In addition, using the individual time series for each of the regions, probability of occurrence of drought for PDSI ≤ -1, ≤ -2, were computed for the periods 1700-1962 (grid S-40) and for 1600-1962 (grid S-50).

Figure 16 shows the lines of equal probability of occurrence of drought with PDSI ≤ -1 as computed for the period 1931-1962.

It is evident that for the majority of the western United States, the probability is greater than 35% that any given July will have a PDSI ≤ -1. The area of greatest probability lies over Utah, Wyoming, Colorado, New Mexico, Arizona, and west Texas. A map for the same period computed from the S-40 tree-ring grid is comparable, showing most of the West with a probability of at least 25% of any July having a PDSI ≤ -1 and the area of greatest probability being in Montana, Idaho, Wyoming, Colorado, and Utah. Figures 17 and 18 are similar to Figure 16, except computed from tree-ring data for the period 1700-1962 (S-40 grid) and 1600-1962 (S-50 grid).

NUMBER OF REGIONS WITH PDSI ≤ -2.0
(i.e. drought intensity greater than moderately dry -- see Table 1.)

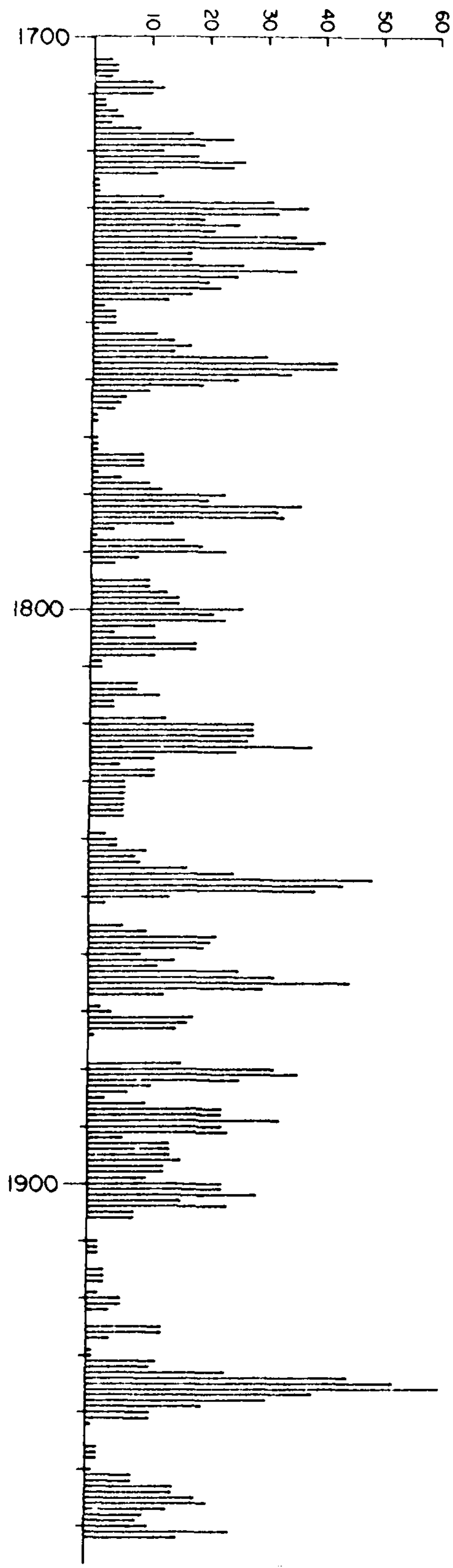


Figure 15. Three-year moving average of regions reconstructed with PDSI ≤ -2 for period 1700-1962 A.D., Grid S-40.

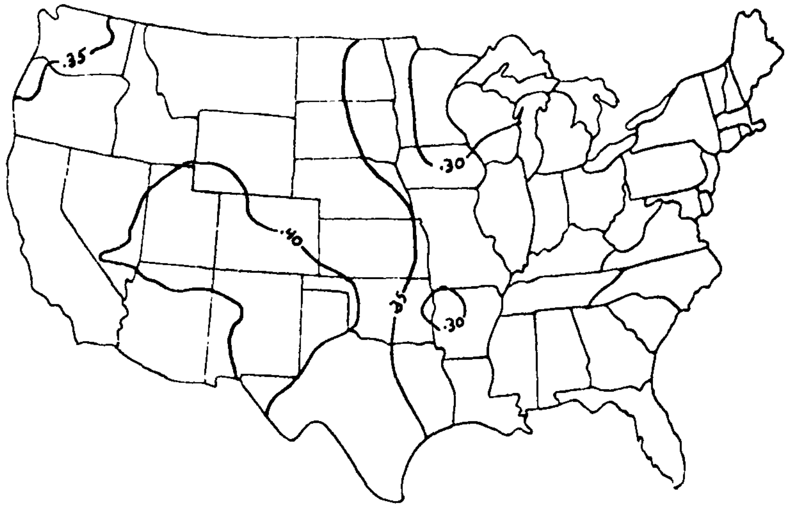


Figure 16. Map of probability of occurrence of July drought with PDSI ≤ -1. Meteorological data for 1931-1962 used in computations.

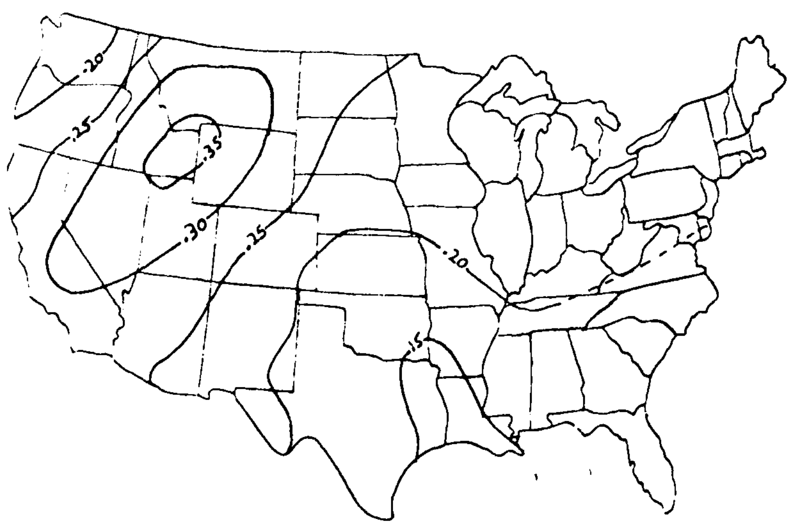


Figure 17. Map of probability of occurrence of July drought with PDSI ≤ -1. Tree-ring data for period 1700-1962 used in reconstruction of drought area.

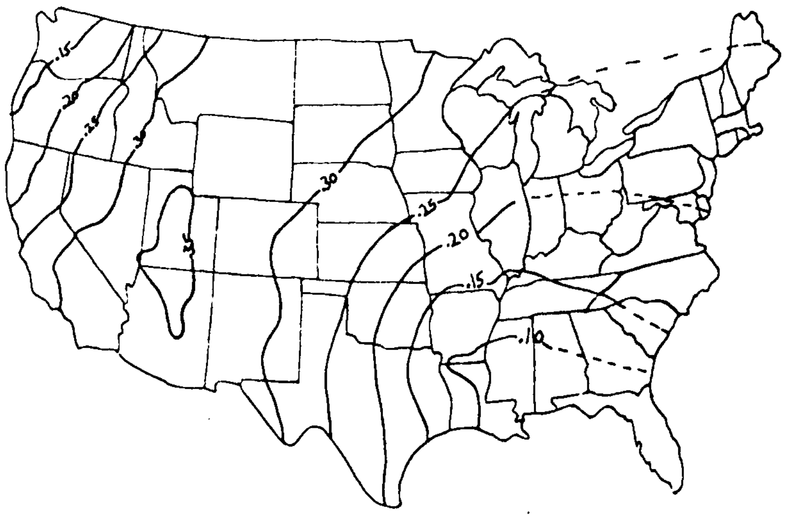


Figure 18. Same as Figure 17 except tree-ring data for period 1600-1962 used in reconstruction of drought area.

Figures 19 and 20 show the results when the PDSI ≤ -2.

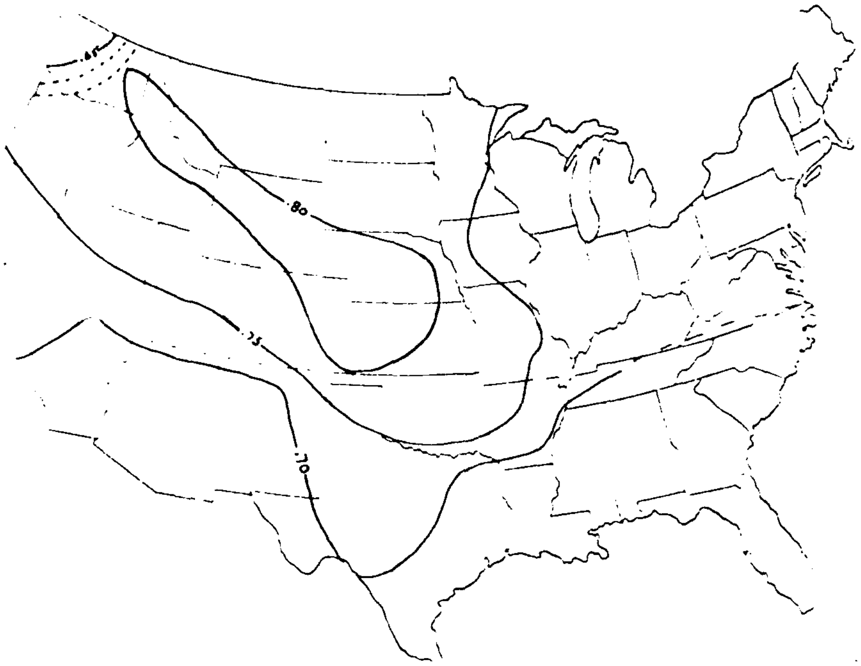
Figure 19. Map of probability of occurrence of July drought with PDSI ≤ -2. Tree-ring data for period 1700-1962 used in reconstruction of drought area.

Figure 20. Same as Figure 19 except tree-ring data for period 1600-1962 used in reconstruction of drought area.

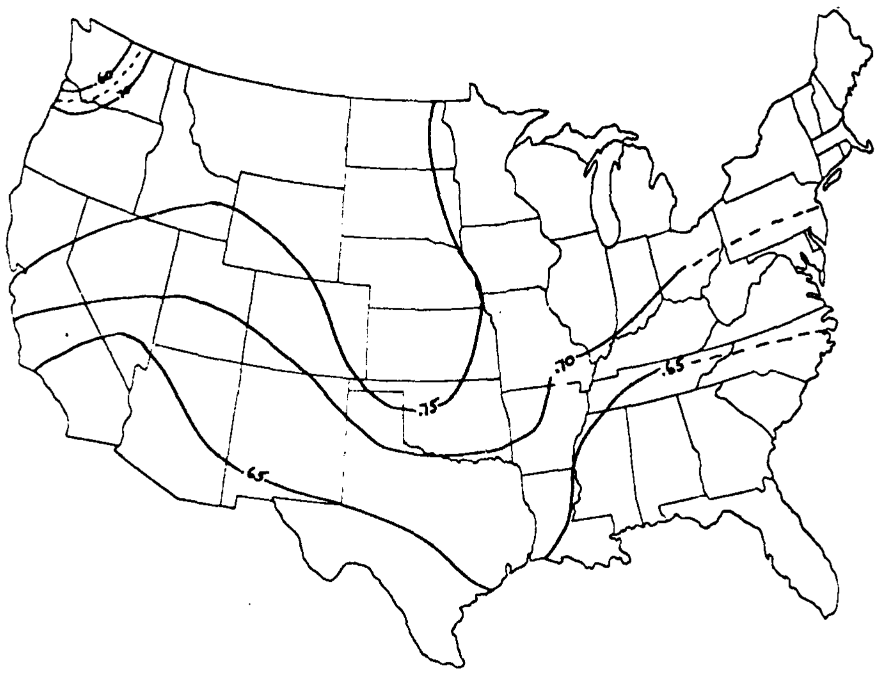
The area enclosed by the 0.3 probability isoline is diminished considerably for the S-40 grid while for the S-50 grid it includes a rather large northeast-southwest trending portion of western United States; note that the S-50 grid extends back to 1600, whereas the S-40 grid goes back to 1700 but the space coverage is greater for the S-40 grid. Both show the region of maximum drought probability extending in a rather large band from the southwest toward the northeast with the probabilities diminishing in a rather sharp gradient towards the northwest and southeast. This generally agrees with an earlier statement that based on atmospheric circulation such conditions might be expected. It is also in general agreement with Julian's (1970) results shown on Figure 13.

Our results also agree with those of Julian concerning the tendency for drought areas to be more consistent than wetter areas. When frequency distribution of the drought areas per unit time for PDSI $\leq -1, -2, -3$ are calculated the results are highly skewed implying a greater tendency for larger areas to be inflicted with drought than to be wet.

A word of caution must be injected at this point. One must remember that the tree-ring data series results from a biological system which acts as a linear filter to given inputs of temperature and precipitation. Although it is highly unlikely that a wide ring would be formed during a drought year, it is also possible that narrow rings associated with severe moisture deficits would not reflect the full intensity of a drought. This is because trees, as biological systems, are time integrators of climatic inputs and thus may tend to "smooth over" some of the inter-annual climatic



(a)



(b)

Figure 21. Maps showing regions of most persistent drought occurrences as expressed by Hurst's k. Larger values indicate greater persistence. (a) is based on 50 year increments; (b) is based on 100 year increments; perior of record 1600-1962.

variations. However, for the PDSI, which is also an integrative process, such "smoothing over" is probably small, perhaps 10 percent or less.

If Hurst's k is indeed a measure of long-term persistence then it follows that based upon a knowledge of atmospheric circulation changes, the value of k might be expected to change accordingly. However, most conventional records are too short to accurately reflect long-term persistence. One of the important questions concerning drought is the delineation of regions of most persistent drought within the United States. For this reason, k was computed for each of the 40 climatic regions based upon the tree-ring derived PDSI records. Utilizing the calculated k values, lines of equal k (iso-k) were constructed for the western two-thirds of the country; the S-50 grid was used in this analysis, so that the longest period is 363 years. Iso-k maps for 50 and 100-year increments were also developed to evaluate the change with record length over the period 1600-1962. The iso-k map for 50 year increments is shown in Figure 21(a). This map is interpreted as showing the persistence in the PDSI series with the greater values representing the regions of highest persistence in drought. Figure 21(b) shows a comparable analysis but for 100 year increments. Both maps show a decrease in drought persistence in the northwest and southeast regions of the United States. The region of greatest persistence (highest k values) varies somewhat but in general includes a rather wide band extending from the northwest to the southeast over the Western United States. The values represent averages for the indicated intervals. In both cases, the values decrease in the northwest-southeast direction. In all three cases, the values are greater than 0.5 suggesting that the occurrence of drought as reflected by the PDSI is not a random phenomenon, although for the 50 year intervals it approaches .55 in the southeastern region.

In summary, these maps suggest long-term persistence in drought is greatest in the central and northern Great Plains Regions, northern Rocky Mountains and Great Basin and the Colorado River Basin. Drought is least persistent in the extreme northwest and southeastern portion of the nation. This is in agreement with earlier stated results and the expectation that the regions of least likely long-term drought persistence are the northwest and southeast.

TOOLS FOR HYDROLOGIC ANALYSIS

Hydrologic processes such as climate, runoff and evapotranspiration tend to behave in a complex manner and a primary objective of the science of hydrology is quantifying their spatial and temporal behavior. As in disciplines such as atmospheric physics, meteorology, fluid dynamics and others, the study of these complex natural phenomena has developed along two distinct lines. Those who have joined together in a deterministic approach attempt to explain hydrologic processes in terms of physical laws. Conversely, the

tendency for random dominance in many hydrologic processes such as streamflow, has led a second group to apply probability theory in an attempt to explain and predict the occurrence of such phenomena. Probability theory, in light of the fact that current knowledge of the physical laws involved are not well understood, affords a way of developing an objective methodology for evaluating the uncertainties and risks involved in hydrologic analysis. The field of stochastic hydrology has developed from the use of probabilistic laws to assess these uncertainties.

Deterministic Hydrology

Todini and Wallis (1977) divide deterministic models into two types. The first are the physics-based models such as that described by Freeze (1972). Freeze describes his model as "a deterministic mathematical model that couples three-dimensional, transient, saturated-unsaturated subsurface flow and one-dimensional, gradually varied, unsteady channel flow. The results of simulations on a hypothetical basin suggest a wide variability in watershed response under the influence of variation in rainfall properties, antecedent moisture conditions, and saturated and unsaturated subsurface hydrogeologic properties." Obviously, the Freeze model should be regarded as a potentially useful approach for studying hydrologic processes on a small watershed approach. However, as pointed out by Todini and Wallis (1977), the model uses complex computer programs involving large storage requirements, almost limitless data, and approximations that tend to pollute the elegant physical detail of the model. Consequently, for modeling rainfall-runoff on large watersheds over long time spans, a second type of model that uses lumped parameters and many simplifying assumptions must be used. Most of these empirical models use an explicit soil moisture accounting technique (ESMA) with variability between models attributable primarily to the simplifying assumptions and lumping parameters.

Seyham (1977) compiled a comprehensive list of climatic, geomorphologic, land use, soil, and runoff variables utilized by various modeling individuals and groups. He also lists the kind of parameter representation (lumped or distributed) used in several models (Table 2).

The number of variables that can, and probably should be included in ESMA type models becomes excessively large. They are consequently lumped, omitted or handled in some other way. The question thus arises as to the appropriateness of the different models to predict runoff for prescribed river basin from given climatic inputs. The World Meteorological Organization (WMO) has compared 10 different models submitted by different agencies from several countries. The results have been published as WMO Operational Hydrology Report No. 7, WMO publication number 429, 1975.

It appears that most discrete time rainfall-runoff models can be classified as explicit soil moisture accounting models. Three of the ten original models tested by WMO were rejected for various reasons. And at least three of the remaining seven were in the general category of ESMA models. A typical flow chart for an ESMA model is shown in Figure 22.

Category	Variables \ Authority	Rational formula	Adams	Besson	Burkli Ziegler, McMath	Craig	Cramer	Gregory, Arnold	Gregory	Grunsky	Hering	Lillie	Possenti	Protodiakonov	Rhind	USSR Academy	Walker	SCS	Chow	Grey and Sherman	Grey (Gamma)	Hickok	Reich	Horton	Erzen	Mamisao	Kinnison and Colby	Potter	Bigwood and Thomas	Morisowa	Benson	Snyder	Jetler	Lucas	Taylor	Wornock	Chen
CLIMATIC	Rainfall intensity																				X			X		X					X						
CLIMATIC	Average intensity				X			X						X		X																					X
CLIMATIC	Maximum intensity	X	X						X	X																											
CLIMATIC	Intensity (30 min. maximum)																						X														
CLIMATIC	Rainfall duration	X						X											X	X				X													
CLIMATIC	Time Distribution																		X					X								X			X	X	
CLIMATIC	Areal Distribution																		X																		
CLIMATIC	Total storm rainfall/area			X		X												X	X				X		X												
CLIMATIC	Mean annual rainfall/area						X					X			X		X																				
CLIMATIC	24 hour rainfall/area												X																								
CLIMATIC	Critical time of rain									X																											
CLIMATIC	Rainfall momentum																																				
CLIMATIC	Impinging angle of rainfall																																				
CLIMATIC	Snow and snow water content															X																					
LAND SURFACE-PHYSICAL / MORPHOMETRIC	Drainage area	X	X	X	X		X	X	X	X	X			X	X	X	X		X	X		X			X		X		X	X	X	X			X	X	X
LAND SURFACE-PHYSICAL / MORPHOMETRIC	Angle of basin sectors											X																									
LAND SURFACE-PHYSICAL / MORPHOMETRIC	Watershed slope		X		X		X		X											X		X	X											X		X	
LAND SURFACE-PHYSICAL / MORPHOMETRIC	Hilly area of watershed									X			X				X																				
LAND SURFACE-PHYSICAL / MORPHOMETRIC	Flat area of watershed									X			X				X																				
LAND SURFACE-PHYSICAL / MORPHOMETRIC	Ratio of total to flat area						X																														
LAND SURFACE-PHYSICAL / MORPHOMETRIC	Drainage density																X			X		X											X			X	X
LAND SURFACE-PHYSICAL / MORPHOMETRIC	Distance to center of gravity																X					X	X				X					X			X		
LAND SURFACE-PHYSICAL / MORPHOMETRIC	Watershed length					X									X											X											
LAND SURFACE-PHYSICAL / MORPHOMETRIC	Channel length							X			X		X	X		X			X		X		X					X		X		X	X	X	X		X
LAND SURFACE-PHYSICAL / MORPHOMETRIC	Sector length											X																									
LAND SURFACE-PHYSICAL / MORPHOMETRIC	Watershed width					X								X		X						X				X								X			
LAND SURFACE-PHYSICAL / MORPHOMETRIC	Elevation difference																									X	X										
LAND SURFACE-PHYSICAL / MORPHOMETRIC	Channel slope							X							X	X			X	X	X		X					X	X		X		X	X	X		
LAND SURFACE-PHYSICAL / MORPHOMETRIC	Watershed shape							X												X										X							
LAND SURFACE-PHYSICAL / MORPHOMETRIC	Surface roughness coefficient			X												X		X	X							X				X							
LAND SURFACE-PHYSICAL / MORPHOMETRIC	Channel roughness							X																X													
LAND SURFACE-PHYSICAL / VEG.&L.USE	Land use																	X	X				X						X								
LAND SURFACE-PHYSICAL / VEG.&L.USE	Forested areas															X																					
LAND SURFACE-PHYSICAL / VEG.&L.USE	Area of lakes and ponds	X		X		X																					X				X						
LAND SURFACE-PHYSICAL / VEG.&L.USE	Volume of depression storage																						X				X				X						
LAND SURFACE-PHYSICAL / VEG.&L.USE	Channel storage																			X				X					X								
LAND SURFACE-PHYSICAL / SOIL	Soil type																		X																		X
LAND SURFACE-PHYSICAL / SOIL	Soil stability																	X																			
LAND SURFACE-PHYSICAL / SOIL	Permeability													X									X	X		X											
LAND SURFACE-PHYSICAL / SOIL	Impervious/pervious area				X		X		X	X								X																			
LAND SURFACE-PHYSICAL / SOIL	Antecedent moisture																	X																			
LAND SURFACE-PHYSICAL / SOIL	Shortest infiltration time															X	X																				
RUNOFF	Ratio of rainfall to runoff							X																													
RUNOFF	Concentration time							X		X																											
RUNOFF	Period of rise																				X																
RUNOFF	Instantaneous discharge																		X	X	X	X	X	X	X	X								X			
RUNOFF	Peak discharge	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X										X	X	X		X	X	X		X		X
RUNOFF	Total discharge/area										X							X												X						X	

Table 2. Hydrologic and climatic variables used in runoff models be various authorities (modified from Seyhan, 1977).

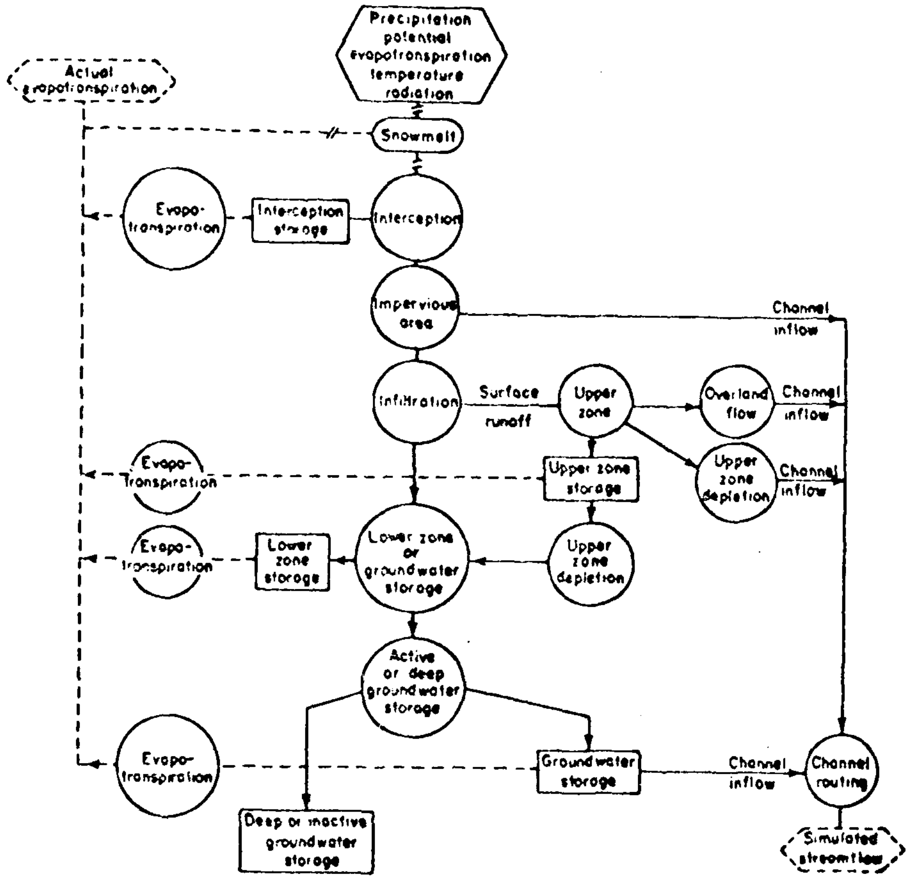


Figure 22. A typical flowchart for a rainfall-runoff model of the explicit soil moisture accounting type, ESMA, redrawn from Linsley and Crawford (1974).

In this case, the soil moisture storage component is modeled by three reservoirs, the upper, lower, and deep ground water storage zones. The channel flow is accomplished by some flow routing scheme with the Muskingum kinematic wave or some empirically derived linear transfer function being applied. Many ESMA models make provisions for multiple sub-basin inflows. Several additional processes (evapotranspiration) can be, and usually are built into the models making the overall response function non-linear in form. One of the models tested in the WMO comparison was a so-called constrained linear system (CLS) type (see Dooge, 1973, for details on these models) utilizing a black box time-invariant non-linear system.

When model divergence (defined as the error variance for forecast flows) is compared between the ESMA and the CLS models by graphical techniques (see WMO Report No. 7) it appears that for more humid regions the CLS model can be as reliable as the ESMA type. For more arid watersheds,

It appears that neither type does a particularly outstanding job. (See comparison graphs on pages 166 and 167 in Todini and Wallis, 1977).

Admittedly, the WMO model comparison study should be viewed in light of its limitations; namely, the comparisons were made on only six watersheds of diverse character. However, based on these findings one might conclude that 1) in many cases a linear system model (as per Dooge and others) can be as effective in flow forecasting as the much more sophisticated and expensive ESMA models; 2) it appears that for more humid climates, both the CLS and ESMA models are useful and appear to make reasonably accurate forecasts of flow from rainfall data; 3) for more arid watersheds, it appears that neither approach is highly accurate. This inaccuracy is perhaps because the models are not adaptable to the full range of climatic possibilities. If an ESMA model is specifically written and "tuned" for a particular arid watershed it will do an acceptable job of forecasting future flows from given climatic inputs.

Stochastic Hydrology

Wallis and Matalas (1972) have shown that expected reservoir performance is conditioned by the assumption of long-term persistence. The presence or absence of long-term persistence can radically alter the design capacity of a reservoir and hence the estimate of firm yield. Hurst, Black and Simaiki (1965) also detail the effect of long-term persistence, especially for the Nile and its effects on storage requirements for the Aswan dam and reservoir. It follows that if long-term peresistence is of such importance, then it is desirable to develop modeling techniques such that synthetic flow traces can be generated and utilized in reservoir models to ascertain the maximum benefit between reservoir size and cost.

Although Hurst was instrumental in developing the relationship between R/S and n^k, it appears that he was unable to develop the mathematical aspects to the point that long-term persistence models were readily available.

Mandelbrot and Wallis (1969) introduced discrete approximation to fractional gaussian noise processes that duplicated the Hurst phenomenon as:

$$X_{(t)} = (h - \tfrac{1}{2}) \sum_{i=t-M}^{t-1} (t-1)^{h-3/2} \, e_{(i)}$$

where M is memory length, h is the Hurst coefficient, and e_i is a Gaussian distributed random variable with zero mean and unit variance. Later work by Matalas and Wallis (1971) showed that the above equation (1) produced first order autocorrelation coefficients (short-term persistence) which were too high to represent annual hydrologic records. They introduced a filtering

parameter into the original equation producing filtered fractional Gaussian noises. These processes have a rather special autocorrelative function in that for large lags, small but non-negligible correlations exist. This produces an autocovariance function that converges to zero for some finite memory, M. However, the limiting autocovariance function obtained as $M \to \infty$ does not converge to zero. Wallis and O'Connell (1973) state that this represents the existence of a very long memory in which the distant past exerts a small but non-negligible influence on the present. This, they say, exhaustively documents that discrete time approximations to fractional Gaussian noise provide a necessary and sufficient explanation for the Hurst phenomenon. From the operational point of view, equation (1) and its modified filtered form are undesirable because of the large summations and resulting high computer costs.

Mandelbrot (1971) subsequently developed a fast-fractional Gaussian noise model consisting of a weighted sum of low frequency and high frequency of Markov-Gaussian processes appropriately parameterized by the value of Hurst's k.

Rodriquez-Iturbe, Dawdy and Garcia (1971) appealed to the notion of nonstationarity in proposing that the Hurst phenomenon could be modeled by adding a nonstationarity term to a stationary process model. They proposed a relationship of the form $R_t \cos (W_t + A_t)$ where the amplitude R_t and phase A_t vary slowly with time t and frequency w. These parameters can be estimated using complex demodulation techniques for nonstationarity series. This technique involves the selection of the appropriate digital filter as is described in detail by Bloomfield (1976). In this case the Hurst coefficient is not explicity modeled but is a function of the filtering technique employed. Anderson (1975) demonstrated the use of this technique on streamflow series.

Another technique for modeling k is the so-called broken line model. According to Kilmartin (1976), the idea for this approach originated with Ditlevsen (1971). It was explored in considerable detail by Rodriguez-Iturbe, Mejia and Dawdy (1972) and Mejia, Dawdy and Nordin (1974). The broken line process results from spanning a trend-line between times t_1 and t_2, with the ordinates at each time determined randomly. For a hydrologic process, the broken line series is a sum of such trend lines where the slopes are randomly determined and of different lengths. The short time spans are related to higher frequency components and the longer increments to low frequency trends. The Hurst effect can be explicitly modeled using parameter estimation techniques for duplicating fractional Gaussian noise.

A similar process for modeling the Hurst phenomenon has been proposed by Klemes (1974) and later by Potter (1976) although the basis for the approach appears to have originated with Hurst (1957). Basically their model is one of shifting the mean for a random process by Monte-Carlo simulation over intervals specified by a preselected probability distribution function. The stimulus for this approach stems from the concept of "almost intransitivity" advanced by Lorenz (1970) to explain the non-linear behavior of atmospheric circulation. Almost-intransitivity describes a system that exists at a given state for some time, t, until by chance it

moves to another state over a short period of time. Apparently both Klemes and Potter feel that the nonstationarity of the mean is a more appropriate explanation of the Hurst phenomenon than the "infinite memory" process accompanying the concept of self-similarity.

Another way of producing the Hurst effect in a time series is through the use of a series of linear stationary models developed by Box and Jenkins (1976). These models, termed ARMA because they merge the concepts of autoregressive (ar) and moving average (ma) models, have received considerable attention in the literature.

A simple first order autoregressive process has been used by many hydrologists to investigate and simulate runoff characteristics. In general, these models preserve the low-order moments well but fail to generate events more extreme than those observed in the historical record. They also do not preserve long-term persistence observed in historical sequences or derived from proxy records.

The algorithm for synthesizing flow records is of the form:

$$X_{(t)} = \rho X_{t-1} + (1 - \rho^2)^{.5} e_t$$

where X_t is the flow at time t with zero mean and unit variance, ρ is the population first order autocorrelation coefficient, e_t is independent and identically distributed random variables with zero mean and unit variance.

There are several different approaches currently in use to simulate runoff records using a first order autoregressive process. Srikanthan and McMahon (1978) recently performed tests to compare the various generation procedures and frequency distributions with the historic traces. The statistics they used to compare the synthetic traces with the historical traces were the mean, coefficient of the variation (standard deviation divided by the mean), the coefficient of skew, and the first order autocorrelation coefficient.

Depending on the magnitude of the skewness and the amount of persistence, Srikanthan and McMahon (1978) found that certain procedures are better than others but the one best procedure is that outlined by Beard (1972). The authors point out that the amount of computer time involved to generate 5000 values by the filtered fractional Gaussian Noise model of Matalas and Wallis (1971) is 200 times longer than that required by the first order autoregressive process. In addition the preservation of low-order moments by filtered fractional Gaussian Noise models is not as good as those preserved by a first order autoregressive model. The generated flows were also less variable than for the historical flows and the Hurst coefficient was not satisfactorily preserved. In their opinion the model is too expensive to run and does not do as good a job synthesizing the historical record as do other models, namely first order autoregressive models.

Burges and Lettenmaier (1977) have also studied and compared different types of models (e.g. short-term and long-term memory). Their study differs from that of Srikanthan and McMahon as they not only compare the ability of the different models to preserve the moments (and other statistics) of the historical record but also the influence on storage demand analysis. Their results suggest that 1) correct modeling of long-term persistence (Hurst effect) will not in itself guarantee an accurate assessment of the storage distribution needed to satisfy a specified demand; and 2) the marginal distribution parameters, coefficient of variation and coefficient of skewness are shown to be important even in cases where substantial long-term persistence is present. For large k, the first order autocorrelation is relatively unimportant as one would anticipate. The value of k is most important at high demand levels. Skewness is most important at moderate values of k and ρ. They also found that the fractional Gaussian noise models had considerable inadequacies as well as quite expensive to operate.

Gomide (1978) presents a case that 1) the Hurst phenomenon can be interpreted as a transient effect of a first order autoregressive process; and 2) that this explanation is far more appealing to engineers than the infinite memory explanation of Mandelbrot and Wallis (1968, 1969a, 1969b). Yevjevich (Colorado State University, 1978, personal communication) echoes Gomide's appraisal of the transient effect of a first order autoregressive process as being the explanation for the Hurst phenomenon.

O'Connell (1974) apparently was the first to carry the Box-Jenkins' modeling approach one step past the first order autoregressive model. He concluded that by adding a moving average component, the Hurst effect could well be duplicated and a long-term persistence built into synthetic traces. Furthermore, O'Connell found that the process could be well duplicated and the Hurst effect preserved by a first order moving average ARMA model of the form:

$$X_t = \phi X_{t-1} + e_t - \theta e_{t-1}$$

where X_t = flow at time t
ϕ = autoregressive coefficient
e_t = independent, identically distributed random variables
θ = moving average coefficient.

The principal disadvantage in the application of the ARMA model is that the Hurst coefficient is not an explicit parameter of the model as it is for the Gaussian noise models. Attempts by both O'Connel (1974) and Lettenmaier and Burges (1977) to establish an equivalency between ARMA model parameters and k have been successful. O'Connell has developed tables relating to Hurst's k to ARMA model parameters. According to Wallis and Matalas (1970), sample estimates of k are biased and so care must prevail if one tries to establish ARMA model parameters for different values of k based on Monte Carlo simulations. Lettenmaier and Burges (1977) recognized the problem of establishing equivalency between k and the ARMA parameters

and developed a ARMA-Markov mixture process that posesses computational simplicity but includes the Hurst coefficient as an explicit parameter. Delleur, Tao and Kavvas (1976) have applied the Box-Jenkins modeling approach to annual, monthly, weekly, and daily series of both streamflow and precipitation. They found that this class of models is satisfactory for preserving the short-term or within year properties of a hydrologic time series but may not be appropriate in preserving the long-term effects at annual level. Therefore, they propose a disaggregation technique which instead of generating events sequentially in smaller time units divides previously generated traces into smaller intervals in time. The technique utilizes a multivariate analysis approach.

Hipel, McLeod and Lennox (1977a) and McLeod, Hipel and Lennox (1977b) describe in considerable detail the procedures in Box-Jenkins' modeling and illustrate the most recent advances with hydrologic examples.

Eagleson (1978) has developed a hybrid model where the input variables are stochastic but their probability distributions are transformed into output variables by using deterministic physical processes. Physically based dynamics and conservation equations are used to define infiltration, transpiration, percolation and capillary rise in terms of independent variables of precipitation, potential evapotranspiration, soil and vegetation properties and water table elevation. Uncertainty is introduced using appropriate probability distribution functions of the independent climatic variables and the dependent water balance elements of surface runoff evapotranspiration and baseflow. The mean values of the output provide a long-term water balance estimate.

Synthetic hydrology helps to overcome the inadequacies and uncertainties associated with the use of historical streamflow data in the design of water resource systems. But, because the history of past flows on a particular reach of a specific stream provides the only available information on the future behavior of the stream, any projections of future flow must be based on the historical record. Synthetic hydrology satisfies the use of the historical sequence to project future flows; although many synthetic flows may be generated, virtually no new information is created. Synthetic hydrology is thus a sophisticated approach to the utilization of information in historical hydrologic records. For this reason, tree-ring data have been utilized as a base from which new information may be derived that is pertinent to hydrology.

Two approaches have been taken in the application of a proxy data series to stochastic analysis of hydrologic processes. The first is the direct technique which uses the tree-ring data base to impart a climatic signal to some reconstructed series of the hydrologic process. Several approaches have been used with different levels of sophistication attached to the final results. The other technique is the use of the long series to derive long-term estimates of parameters that reflect the climatic signal. An example is Hurst's use of tree-ring series (and other proxy data) to evaluate the divergence of k from the theoretical k = .5 law.

In addition to Hurst, application of secondary series such as tree

rings to estimate the Hurst phenomenon has been made by Mandelbrot and Wallis (1969). Hipel (1975) utilized tree-ring data to derive improved estimates for his ARMA model parameters. Lettenmaier and Burges (1978) following the lead of Hipel also utilize tree-ring data series to develop long-term model parameters for ARMA models and to test for nonstationarity of means and variance.

A host of early researchers, Hardman, Reil (1936), Keen (1937), Schulmann (1945a, 1945b, 1947, 1951), Potts (1962), Gatewood, Wilson, Thomas and Kister (1964) have studied the relationships between precipitation, runoff, and tree rings concluding tree-ring data can be a usable proxy series for improving hydrologic estimates.

More recently, Stockton and Jacoby (1976) re-examined the long-term flow of the Upper Colorado River based on tree-ring data. This analysis was based on considerably more tree-ring data than had been previously used and utilized modern multivariate time series techniques in addition to the more traditional approaches such as variance spectral analysis. The results show that for at least the Upper Colorado River, utilization of a proxy series such as tree-ring series can supply new and useful information for hydrologists. Improved estimates of the annual mean flow, annual variance and long-term persistence can be obtained. In addition, real time estimates of past flow can be made.

The probablistic hydrology approach is not concerned with time sequence but only with probability, or chance, that an event will be equalled or exceeded. In stochastic and deterministic hydrology the time sequence is all-important and therefore they are the most appropriate models for evaluating the time series properties incorporating climatic change. In probablistic studies, the assumption is that time series properties do not change with time and therefore these techniques in themselves are not as appropriate as either the deterministic or stochastic approaches for evaluating climatic variability and its affect upon hydrologic processes.

ANALYSIS OF RELIABILITY OF ANALYTICAL TECHNIQUES

Since it is apparent that the exact sequence of future streamflow or any other hydrologic process cannot be predicted it is imperative that some approach be devised to evaluate probable future variations and design completed on the basis of calculated risks. The historical flow record (if one is available or can be interpreted from nearby records) can be used to construct flow-duration curves, complete probability studies and develop storage-yield curves. These results are consequently used in design decisions.

Storage-yield curves are developed to assess the risk that a reservoir will not meet a prescribed level of demand. The risk is a function of streamflow into the reservoir, storage capacity and demand characteristics and usually is determined by performing many trials of reservoir operation. In many cases, the storage-yield for a given site is determined from historical streamflow data. Consequently, the capacity of the reservoir to meet projected demand is intimately tied to the nature of the historical record and its ability to reflect future flows. As previously pointed out, many techniques presently used assume the flows to be random in time and standard statistical methods are used (see for example Methods of Flow Frequency Analysis, 1966, Subcommittee on Hydrology, Inter-Agency Committee on Water Resources). If the life time for the structure is say less than 30 years, ~~ere~~ There is a high probability that the assumption of randomness of the historical record -- if about 30 years in length -- will be approximately correct. But for longer life spans, as we have pointed out earlier, the assumption may be in gross error. One way to approach the problem is to use one of the deterministic or stochastic hydrology approaches to create long term synthetic hydrographs and use them as inputs into a reservoir operation simulation study. If the appropriate model is chosen, the historical record can be assessed and risks evaluated based on known time series characteristics. As has been shown, there are a multitude of models that can be used.

However, it becomes quite apparent after reviewing recent literature, that there is no "best" model or technique for estimating the climatic effect on hydrologic processes. The deterministic modeling approach appears to be muddled in light of the recent WMO investigation of different models discussed earlier. The test results suggest that in many basins, a linear systems model using classic least squares analysis provides as reliable results for forecasting continuous flow records as does the much more sophisticated explicit soil moisture accounting models.

If the state-of-the-art in the deterministic modeling field seems muddled, then that in the stochastic modeling field is even more so. The controversy over the so-called Hurst phenomenon continues to hold the limelight. The question of nonstationarity especially in the mean but also in the variance of runoff records still seems to be in question. Many still believe that nonstationarity is the explanation for the Hurst ~~ect~~ Effect. If this is so, then the use of many models that utilize the ~~licit~~ Explicit assumption of stationarity become highly questionable. The so-

called ARMA models are in this category. The use of fractional Gaussian Noise models, and the several modifications thereof, are not as universally acceptable as they were originally hoped to be. The cost of utilizing them is great and the results are not as appealing as hydrologists had hoped.

At this time, synthetically derived streamflow records, based on the application of a first order Markov process, have considerable appeal primarily because the procedure is economically reasonable to use even though long-term persistence is not imparted to the synthetic traces. Also certain statistics must be estimated from historical records which may not be representative of future flows.

Of particular concern in the analysis of storage-yield relationships are the duration of low flows and the mean annual flow. If the longest low flow period in the historical record is a good representative sample of that which may be expected to occur in the future and the mean is also representative, then the yield risk can properly be assessed. Obviously, the longer the record the more likely it can be assumed that the record is representative.

It is not difficult to see that the degree of persistence in streamflow -- especially in high and low flows is critical in reservoir design. Hurst's k is a quantitative measure of this persistence. By using a model in which Hurst's k is an explicit parameter, synthetic hydrographs can be generated and evaluated allowing evaluation of long-term persistence and its affect on reservoir operation. But as previously stated, this is not a simple procedure. As Lettenmaier and Burges (1978) point out:

> "Insofar as modeling nonstationarity in the mean (flow) is concerned, it is clearly premature to make use of models incorporating time-varying means and residual short term noise in design or analysis of water resources systems. On the basis of current work, it is unlikely that a data-based approach will prove fruitful in this respect. Ultimately, better knowledge of the dynamics of climate and climate change may be reflected in long range predictive ability for streamflow processes. At that time, it will be necessary to incorporate such understanding in streamflow generation mechanics. In the interim, closer interaction between hydrology and climatology (hydroclimatology?) is necessary."

Consequently, the reliability of storage-yield analysis based on existing short-term records without due consideration of climatology and evidence of climatic variability from existing proxy records is doubtful.

In light of the outcome of this study and others (e.g. Fritts and Lofgren, 1978) regional correlation techniques must be restricted to areas of climatic homgeneity. Through the use of proxy records, maps such as those presented in Figure 21 and the use of statistical techniques such as those defined by Julian (1970) can be utilized to define areas of estimated climatic homogeneity. The techniques utitlized in the estimation of flow records for ungaged sites must be chosen so that they incorporate the

climatic characteristics of the region and duplicate the time series properties of the basic generating process. In some cases, the first order Markov process may be appropriate, however, in many cases it may be necessary to use a ARMA model (or an analogous model) in order to incorporate the necessary long-term persistence into synthetic traces.

The question concerning the probability analysis techniques utilized in storage-yield curves, the validity of analytical and graphical frequency curve analysis for high and low flows must be related directly to the crucial assumption of time independence of the assumed probability distribution factor and its mean, variance, skewness and kurtosis. By comparing the time series upon which these assumptions are based with a comparable much longer series reflecting climatic variability, a researcher can ascertain, at least qualitatively, the representativenss of the historical gaged record. Deviations from the historical record in light of comparison with other records can then be incorporated into simulation studies and the necessary system operation resiliency considered in future decisions.

Evaluation of changes in precipitation variability and its effect on reliability of flow frequency analysis will vary from basin to basin and region to region. Insight into these changes can possibly best be evaluated using the deterministic type models to simulate the precipitation-runoff relationship in which variability of precipitation is changed and the resulted runoff series generated. The result will then be based on the adequacy of the precipitation-runoff model.

APPLICATION TO THE INDIVIDUAL
WATER RESOURCES REGIONS OF CONTERMINOUS UNITED STATES

As pointed out earlier, it should not be anticipated that the climatic effect on hydrologic processes, primarily surface runoff, would be uniform throughout the Nation. For this reason, we will analyze and qualitatively forecast (speculate) the anticipated effect of climatic variation on a region-by-region basis. Since the Water Resources Council (WRC, 1978) has already established water resource regions that approximately coincide with river basin boundaries, and because river basins to a certain degree represent "homogenous" climatic regions, it follows that these regions would be applicable to this study. The 18 regions which are within the conterminous United States are shown on Figure 23.

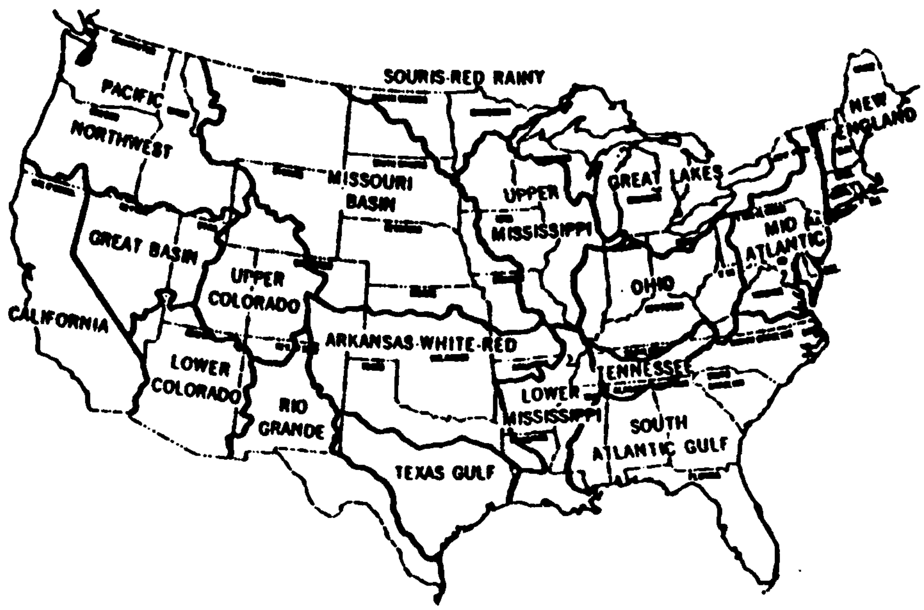


Figure 23. Eighteen major water regions within conterminous United States as defined by the U.S. Water Resources Council.

Each region will be analyzed separately and evaluated as to postulated effects of 4 climatic scenarios on various parameters of major concern in water resource planning. The four scenarios include: 1) an <u>increase</u> in mean annual temperature of 2 degrees Celsius, with an associated <u>decrease</u> in mean annual precipitation of 10% (warmer/dryer); 2) a <u>decrease</u> in total annual temperature of 2 degrees Celsius with an associated <u>increase</u> in total

annual precipitation of 10% (cooler/wetter); 3) an increase in mean annual temperature of 2 degrees Celsius associated with an increase in total annual precipitation of 10% (warmer/wetter); 4) a decrease in mean annual temperature of 2 degrees Celcius with an associated decrease in total annual precipitation of 10% (cooler/dryer). In most cases, only scenarios 1 and 2 were determined to be important. For the other two cases, it is postulated that the net increase or decrease in temperature will result in a net change in evapotranspiration that will essentially offset the net gain or loss from the change in precipitation. It has long been recognized that mean annual runoff equals total precipitation minus losses due to evapotranspiration plus or minus the net change in ground water storage. The loss due to evapotranspiration is primarily a function of temperature and water availability. In more humid regions, where water is not limiting, evapotranspiration is primarily controlled by temperature. The result is, that in temperate and humid areas, the difference between long-term precipitation and runoff can be very closely related to temperature. Figure 24 from Langbein and others (1949) shows the relationship between mean annual temperature and evapotranspiration. Obviously, the greater the mean annual temperature, the more effect an equivalent change in temperature will have on evapotranspiration. Consequently, one would anticipate greatest effect of a two-degree change in temperature on annual runoff to be within the more southerly latitudes of the United States.

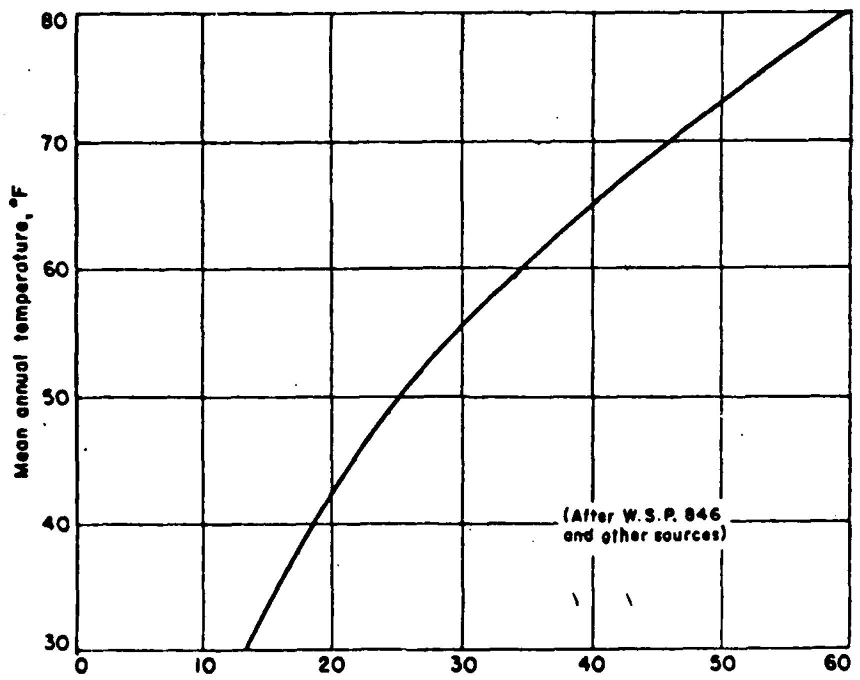


Figure 24. Relationship of annual evapotranspiration loss in humid areas to temperature. After Langein and others (1949).

It follows, that a more generalized evaluation of climate upon runoff might be based on the assumption that for a given combination of annual rainfall and temperature, a given runoff amount will result. Langbein and others (1949) investigated this relationship based on representative data from 20 catchments throughout the conterminous United States. Humid to arid and cold to warm regions were included. A weighted mean temperature was computed by dividing the sum of the products of monthly precipitation and temperature by the annual total precipitation. The quotient provides a mean annual temperature in which the temperature of each month is weighted in accordance with the precipitation during that month. A weighted mean temperature greater than the mean temperature indicates that precipitation is concentrated in the warm months, whereas the opposite indicates precipitation concentrated in the colder months. For example, in the Upper Mississippi River drainage, the greatest monthly precipitation occurs in June, July and August. The average annual temperature varies from 55° F in the southern part to 45° F in the northern part. The weighted mean annual temperature, however, varies from 56° F in the southern portion to 55° F in the northern part. In the Pacific Northwest Region, along the eastern and southern boundaries, the precipitation is distributed uniformly over the year and the weighted temperature is slightly lower than the mean annual temperature. However, along the western edge, the precipitation comes primarily in the winter and the weighted mean temperature of about 45° F is substantially less than the mean annual temperature of 50° F. The difference, then is measure of the concentration of precipitation in the warm months or cold months of the year. It is clear that a climatic aberration involving a change in the monthly distribution of precipitation has large effects on the total annual runoff. Figure 25 shows a plot of mean annual total precipitation versus mean annual total runoff as a function of weighted mean annual temperature in degrees Fahrenheit. These graphs illustrate how the runoff for a given total precipitation decreases as the mean annual weighted temperature increases. Also, for a given temperature, runoff increases with precipitation. The numerical difference between precipitaion and runoff for a given temperature likewise increases with precipitation, ultimately reaching a constant representing optimum evapotranspiration. This assumes that evapotranspiration is solely controlled by temperature (solar radiation) and water availability. Although evaporation is affected by other factors such as wind movement and relative humidity, their effects tend to average out over large areas.

It is apparent that many physical factors may alter the effect of climate upon the total annual runoff. These include, among others, geology, topography, size of drainage basin, and vegetation (see Table 2 for more). As pointed out in the section on deterministic modeling, many of the more sophisticated models (e.g. Eagleson, 1978) attempt to incorporate the minute effects of many of the less obvious variables. When precipitation and temperature functions are used to estimate annual runoff (as in Figure 25) it is important to assess, at least qualitatively, the physical aspects of the region. For example in some volcanic terrains, (e.g. the basaltic plains of Idaho, Oregon, California and New Mexico) virtually no surface runoff occurs although the total precipitation may reach 200 inches per year. Another case is the southern High Plains area where the highly permeable Ogallala formation absorbs a large portion of

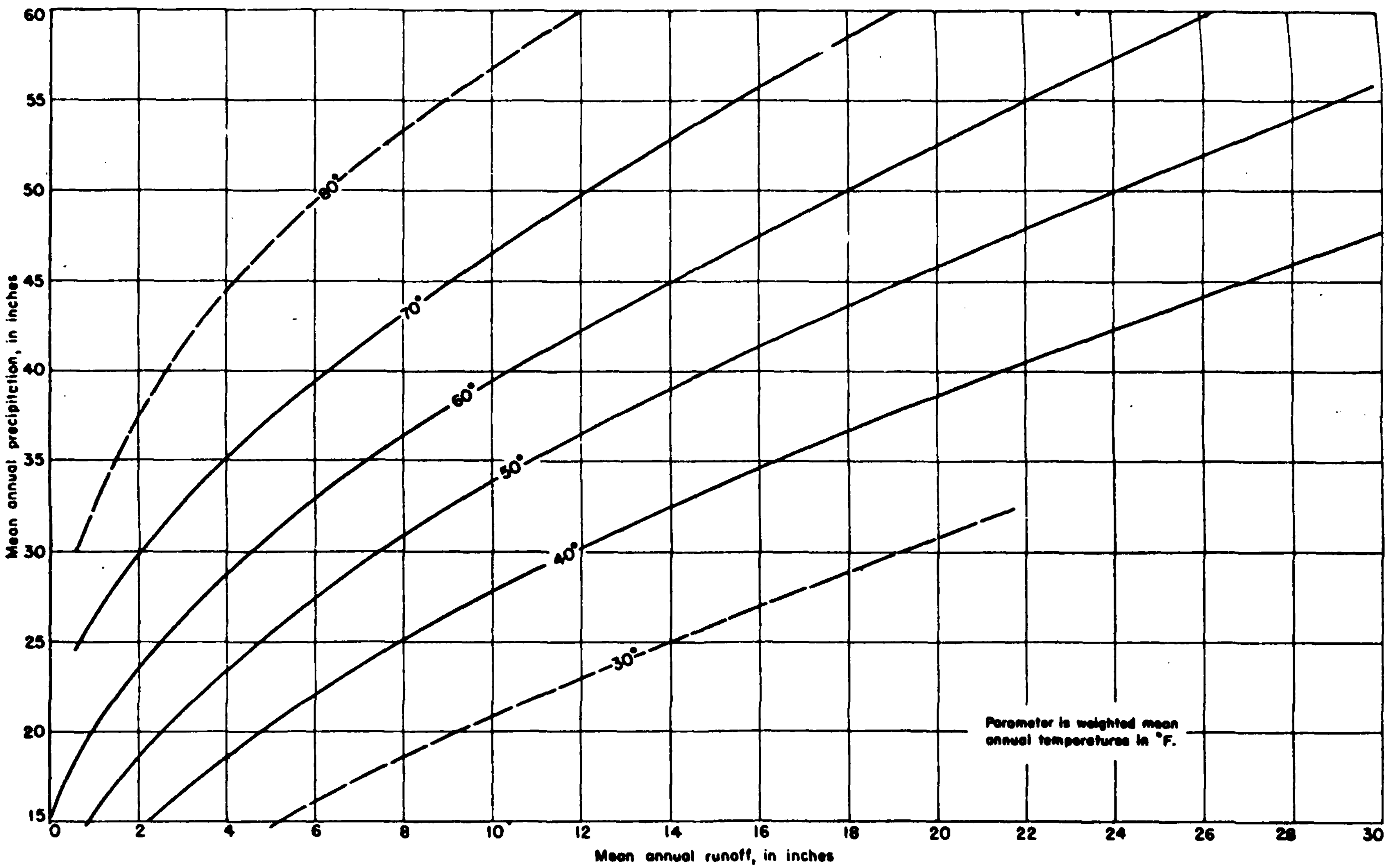


Figure 25. Relationship of annual runoff to precipitation and temperature. After Langbein and others (1949).

the surface runoff creating an apparent anomaly between climate and runoff. The relief of the land has a pronounced effect in the occurrence of runoff. It is well-known that an increase in precipitation and decrease in temperature accompanies a marked increase in runoff with altitude at least as high as the snow line.

Surface runoff is generally conditional, to some extent, on the geology. The physical nature of a catchment is reflected in the time series of streamflow -- for example, the time to peak runoff from a basin varies with the parameters of the basin. In some cases, the soil mantle and exposed rock outcrops have a tremendous capacity for water storage. In others, the surface area of a basin is impermeable and the streamflow tends to recede rapidly from concentrated flood peaks to low flow. The shape of the drainage network is also a variable related to the geology. However, as pointed out by Langbein et al. (1949), the storage and timing factors related to the geology of a basin, is thought to have only indirect effects on the volume of total annual runoff.

A flow chart was devised (Figure 26) to implement regional analyses. The general approach, as reflected by the flow chart was to:

1. establish the present hydrologic state of the system by evaluating the various physical factors just discussed;

2. superimpose the various climatic forcing functions, as described by the four scenarios, upon the present system; and

3. evaluate the effect of these postulated changes in a speculation impact matrix (Schwarz, 1977).

The speculation impact matrix is an attempt to relate various qualities of the time series of streamflow that are reflective of climatic variability (columns) to the effects on regional water quantity, quality, engineering structures, demand and costs of operation (rows). Consequently, the final numerical impact weight is related to climatic variability as reflected through various streamflow characteristics and their impact upon regional water supply, demand and cost.

A 9-row x 6-column speculation matrix was developed for each nontrivial climatic scenario that appeared to have either positive or negative effects in each of the 18 WRC regions. A verbal summary of the effects is given in each of the 54 matrix cells. In addition, a numerical evaluation was made for each of the nine water resource categories (rows) of the matrices by assigning relative weights ranging from -4 for negative impacts to +4 for beneficial impacts. These ratings were summed algebraically to obtain the total impact for each given climatic scenario. The adverse effects range from -1 to -36 and positive effects from +1 to +36. Impact categories were then developed as shown below:

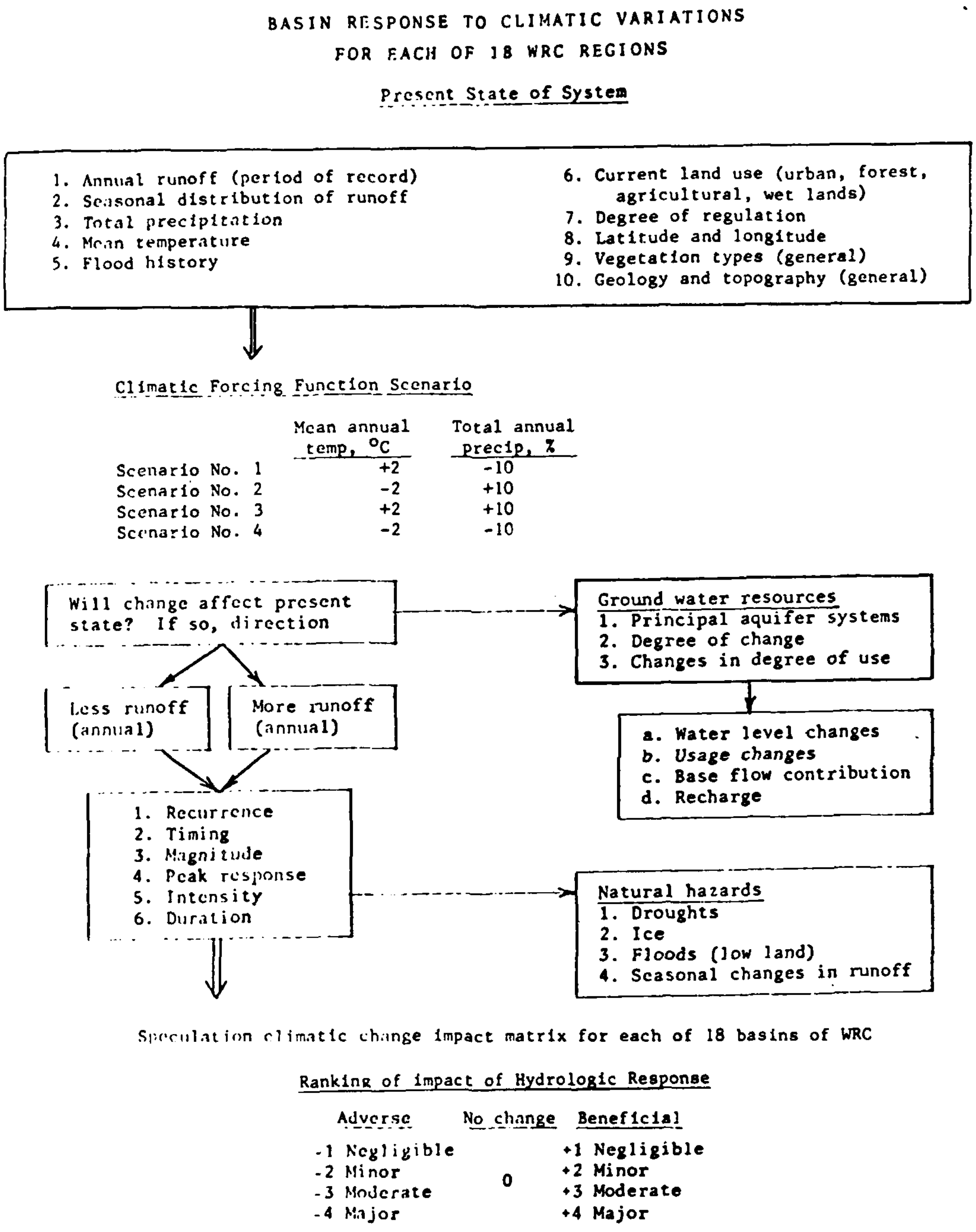


Figure 26. Information flow for evaluation of climatic change on each water resource region.

Adverse Impacts	Beneficial Impacts
-1 to -9, Negligible	+1 to +9, Negligible
-10 to -18, Minor	+10 to + 18, Minor
-19 to -27, Moderate	+19 to +27, Moderate
-28 to -36, Major	+28 to +36, Major

The various regions were then classified according to the adverse or beneficial impacts, tabulated as described above.

The total score that each region received is highly dependent upon the individual assigning the relative weights. But the general philosophy underlying the weighting decisions was that climatic variability is most important in regions where demand is large relative to supply. If the total water available after the occurrence of the postulated climtic change was appreciably greater than anticipated total withdrawals, then engineering and construction could be undertaken to alleviate problems of local shortages, pollution and navigation. The potential available ground water resource, and its conjunctive use with surface water was also a major consideration in assigning the relative severity of the impact. If, for example, a region's current total runoff is almost totally committed and ground water is being heavily mined, the system is considered to be currently stressed and any reduction in total annual runoff would be adverse to water resource management. If the water doesn't exist, there are no engineering or construction solutions to the regional shortage. Conversely, if a region is already water-rich and a scenario 2 type climatic change increased the mean annual runoff by an appreciable amount, the present system would probably not be reliable for flood control and low lands would be inundated. This type of change would be quite beneficial to water short regions, however.

The regional runoff response to postulated climatic change was evaluated by using the curves developed by Langbein _et al_ (1949) that show the relationship of annual runoff to precipitation and temperature (Figure 25). Using these curves, ratios were developed expressing the estimated mean annual runoff under assumed climatic change (Q scenario) to present values (Q present).

Temperature and precipitation data from selected stations within each region were used as a basis for estimating the mean annual runoff and developing the Q scenario/Q present ratios described above. In some regions, there was considerable variation in the climatic data from different stations and the resulting regional runoff estimates seemed unduly weighted toward the extremes. For such regions the runoff ratios were calculated by using both the individual station records and their averages.

Assumptions

In estimating the effects of the climatic change scenarios on mean annual runoff on a region-by-region basis, the following assumptions are made:

1. The region-by-region variation in annual runoff is predominantly influenced by climate although other factors such as geology, topography, vegetation and many other variables may be important especially in smaller drainages.

2. The empirically developed curves associating total annual precipitation and total annual runoff with weighted mean annual temperature are appropriate for all 18 regions although derived from a relatively small (22 drainage basin) sample.

3. Changes in land use have relatively small influences on region-wide annual runoff.

4. Annual runoff is not greatly affected by large scale ground water overdraft.

5. Evapotranspiration is controlled solely by temperature.

6. Postulated climatic change scenarios do not modify present monthly distribution of temperature and precipitation but only amplitude of present distribution is increased or decreased.

7. Selection of a few meteorological stations for each region provides adequate control for establishing the weighted mean temperature and annual precipitation relationship to annual runoff.

Data used in the analyses and discussions of the individual regions were obtained from a variety of sources. Most of the estimates for water supply and depletion, and general descriptions of the regions, came from the U.S. Water Resources Council, Second National Water Assessment, (1978). Evaluations of ground water conditions were obtained from U.S. Geological Survey Professional Paper 813, if the appropriate chapter had been completed. Otherwise, USGS Water Supply Paper 1800 (McGuinness, 1963) was used. A complete list of the sources is shown below.

Baker, E. T. and J. R. Wall, 1976. Summary appraisals of the nation's ground water resources - Texas-Gulf region. U.S. Geol. Survey Prof. Paper 813-F, 29 pp.

Bedinger, M. S. and R. T. Sniegocki, 1976. Summary appraisals of the nation's ground water resources - Arkansas-White-Red region. U.S. Geol. Survey Prof. Paper 813-H, 31 pp.

Bloyd, R. M., Jr., 1974. Summary appraisals of the nation's ground water resources - Ohio region. U.S. Geol. Survey Prof. Paper 813-A, 41 pp.

Bloyd, R. M., Jr., 1975. Summary appraisals of the nation's ground water resources - Upper Mississippi region. U.S. Geological Survey Prof. Paper 813-B, 22 pp.

Eakin, T. E., D. Price and J. R. Harrill, 1976. Summary appraisals of the nation's ground water resources - Great Basin Region. U.S. Geol. Survey Prof. Paper 813-G, 37 pp.

McGuinness, C. L.. 1963. The role of ground water in the national water situation. U.S. Geol. Survey Water Supply Paper 1800, 1121 pp.

Price, D. and T. Arnow, 1974. Summary appraisals of the nation's ground water resources - Upper Colorado region. U.S. Geol. Survey Prof. Paper 813-C, 40 pp.

Reeder, H. O., 1978. Summary appraisals of the nation's ground water resources - Souris-Red-Rainy region. U.S. Geological Survey Prof. Paper 813-K, 25 pp.

Sinnott, A. and E. Cushing, 1978. Summary appraisals of the nation's ground water resources - Mid-Atlantic region. U.S. Geol. Survey Paper 813-E, 54 pp.

Thomas, H. E. and D. A. Phoenix, 1976. Summary appraisals of the nation's ground water resources - California region. U.S. Geol. Survey Prof. Paper 813-E, 54 pp.

U.S. Water Resources Council, 1978. The nation's water resources: The second national water assessment by the U.S. Water Resources Council, U.S. Water Resources Council, Washington, D.C.

Weist, W. G., Jr., 1978. Summary appraisals of the nation's ground water resources - Great Lakes region. U.S. Geol. Survey Prof. Paper 813-J, 30 pp.

West, S. W. and W. L. Broadhurst, 1975. Summary appraisals of the nation's ground water resources - Rio Grand region. U.S. Geol. Survey Prof. Paper 813-D, 39 pp.

Zurawski, A., 1978. Summary appraisals of the nation's ground water resources - Tennessee region. U.S. Geol. Survey Prof. Paper 813-L, 35 pp.

REGION 01 - NEW ENGLAND

The New England Region encompasses 69,003 square miles and includes the states of Maine, New Hampshire, Vermont, Massachusetts, Connecticut, Rhode Island and parts of New York (Figure 27). Although the region contains some of the most densely populated land in the United States, rural and even wild sections are within commuting distance of some major cities.

Normal annual precipitation ranges from about 36 inches to near 50 inches for isolated areas near the central and southern portions of the region. In the north and central parts, precipitation is greater during the summer and fall seasons than in the winter and spring. In the southern portion rainfall is fairly evenly distributed throughout the year.

Mean annual temperature ranges from near 38°F. in the northern part to near 50°F. in the more southern portion. The comparable weighted mean annual temperatures (as defined by Langbein and others, 1949) range from near 45°F. in the north to near 50°F. in the southern portion.

Most of the area is forested with about 75 percent covered by spruce, fir, northern hardwoods and oak-hickory forests. About 10 percent is cropland and pasture of which only 1.5 percent is irrigated cropland. About 6 percent is occupied by urban and built-up areas. Water surface, lakes, ponds, etc., make up about 6 percent of the total area.

The region consists of mountains, upland plateaus, and low-land plains ranging in elevation of from sea level to 6300 feet. The major rock types are primarily metamorphic and igneous although some sedimentary rocks underlie the Connecticut Valley.

Glaciation was a major factor in shaping the topography of the region. Extensive deposits of glacial till, ranging in thickness to over 100 feet, occupy the valleys and areas along the coastline.

Ground water is not a major source of water in the region. Estimated use in 1975 was about 0.6 bgd or 0.7 maf per year.

In Connecticut, ground water is produced primarily from glacial deposits, especially stratified drift. Yields are small and large diameter wells are common. The water table is shallow and consequently easily contaminated and affected by drought. Bedrock is low to moderate in productivity. Heavy pumping along the coastal areas is resulting is salt water encroachment. The ground water situation is similar in Maine with exception that wells in limestone deposits in the eastern part yield up to 300 gpm. In Massachusetts, yields vary from small to large with the larger production coming from glacial drift in lowlands of the eastern part and in the Connecticut Valley. In New Hampshire, the average permeability of the bedrock is quite low and well yields are small. In Rhode Island small amounts of ground water are produced from bedrock and till sources. Some salt water encroachment is threatening along the coast. In Vermont, ground water occurs principally in fractured crystalline rock; yields

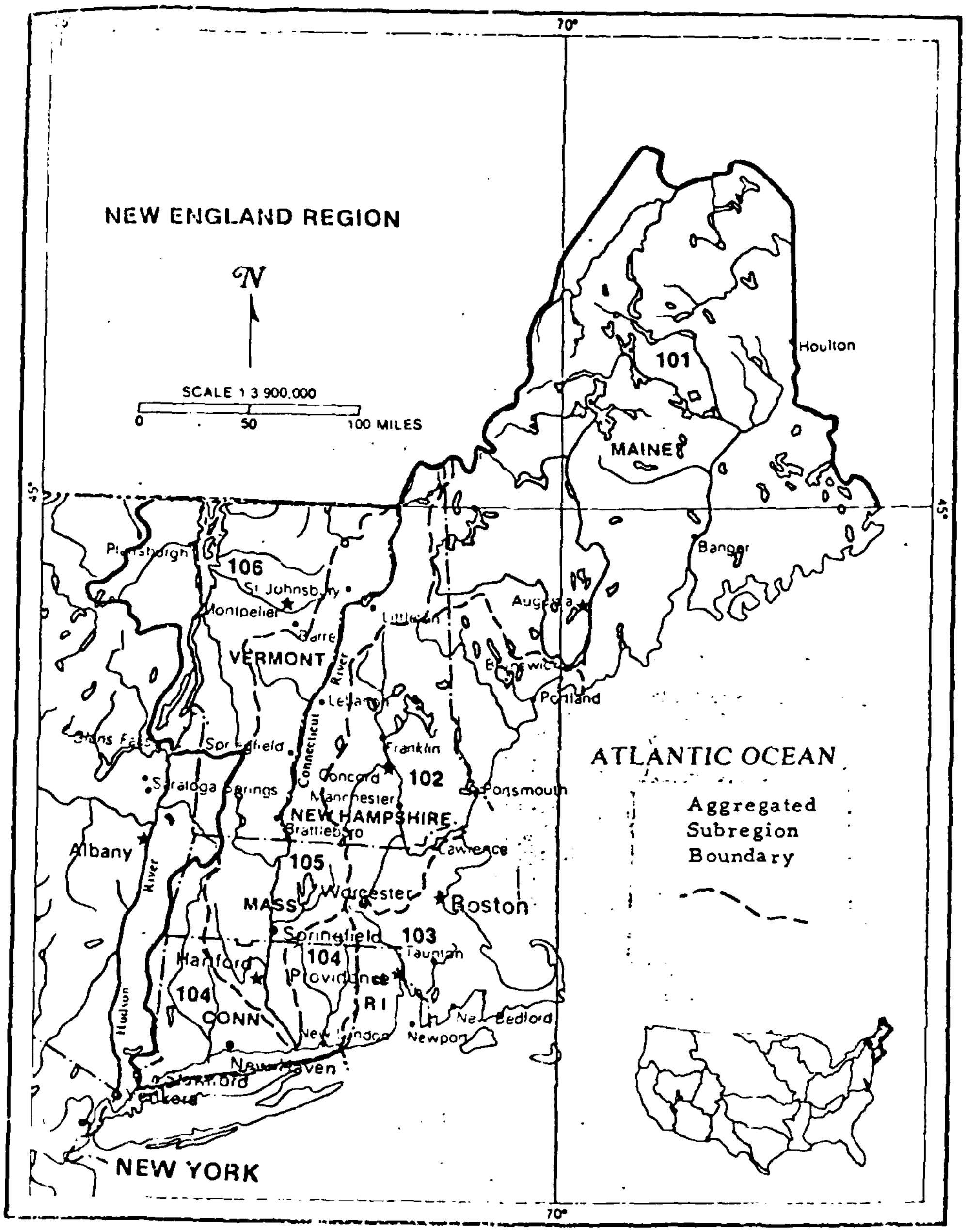


Figure 27. Location and drainage of the New England Region

to wells are generally small except along larger streams where they may be moderate to large. Carbonate rocks supply some water to wells in the lowlands and the Piedmont area.

The average annual runoff from this region is estimated to be 78.6 bgd (88.0 maf). As of 1975, only about 1 percent of the runoff is actually consumed within the region, although it is estimated that 69.0 bgd (77.3 maf) are required for fish-wildlife and recreation. The present (1975) mean annual outflow from this region is 78.1 bgd (87.5 maf) and the median is 77.4 (86.7 maf). The 5 percent exceedence is 107.7 bgd (120.6 maf) and the 95 percent is 48.3 (54.1 maf). The ratio Q_{05}/Q_{95} is 2.2. The average annual flow and the median are very nearly the same indicating the flow is normally (Gaussian) distributed. The monthly distribution of flow shows that in the northern portion of the region, peak runoff occurs during April and May, while in the southern part of the region the peak comes in March or April.

There is no significant trend in the annual surface runoff values over the period 1903-1977 in any of the six subregions. As of 1975, streamflows within the region were far greater than withdrawal and consumption requirements. Regulations concerning water quality are expected to be increased as pollution is a major concern. In no case, either presently or in the future are withdrawals expected to cause streamflow in the New England Region to fall below 60 percent of their present natural flows. Local variation due to regulation may decrease flows within individual basins. There are approximately 3000 dams in the region and most are single purpose in nature. About one-half (1500) are for recreation, 300 for flood control and 700 for water supply. Fewer than 300 produce electric power.

Given the present climatic regime of the region, the four climatic scenarios were superimposed to estimate resultant hydrologic changes. Climatic data from Boston, Massachusetts, Burlington, New Hampshire and Caribou, Maine were used to develop the $\overline{Q}$ scenario to $\overline{Q}$ present ratios shown in Table 3.

Scenario	South	Central	North	Average
1 (warmer and drier)	.73	.72	.70	.72
2 (cooler and wetter)	1.35	1.35	1.43	1.38
3 (warmer and wetter)	1.03	1.05	1.11	1.06
4 (cooler and drier)	.97	.95	.91	.94

Table 3. Ratio of $\overline{Q}$ scenario/$\overline{Q}$ present for the New England Region for each of the four climatic change scenarios in the south, central, and the northern parts and their average for the region.

It is apparent from Table 3 that only scenarios 1 and 2 are significant and that scenarios 3 and 4 are trivial. Apparently the changes in precipitation and temperature are compensating in that the changes in water availability (precipitation) are compensated for by demand (evapotranspiration) resulting in little if any change in runoff. The speculative impact matrices for scenarios 1 and 2 are shown in Tables 1 and 2 in the Appendix.

The occurrence of a warmer and drier climate is conjectured to result in a regional reduction of 30 percent in the present mean annual runoff. But because the present and projected future demand is 60 percent of the present, it is our opinion that the 30 percent reduction would create local shortages but not large scale region wide shortages. The greatest effect assuming present rate of pollution continued would be increased pollution as the number of low flow days per year would increase. Overall, this region would not be seemingly affected by the occurrence of a scenario 1 type climatic change. A cooler and wetter (type 2) climatic variation would result in an increase of 35 to 40 percent above the present mean annual runoff. Although risk of flooding, especially in the low lands and flood plains would be incurred, the higher sustained flow could be advantageous in the removal of industrial and municipal wastes causing an improvement in water quality. Because flood protection is minimal in the region, without larger reservoir storage for the greater high flow, flooding would cause an increase in annual losses. The overall regional impact of a scenario 2 climatic variation would be minimal.

REGION 02 - MID-ATLANTIC REGION

The Mid-Atlantic Water Resources Region includes several independent drainage basins flowing into the Atlantic Ocean from the Hudson River in the north to the James River in the south (Figure 28). The total drainage area is about 103,342 square miles which includes some two million acres of inland water surface and an additional 24 million acres in bays and estuaries. More people are concentrated in the Middle Atlantic Region than any other region of the United States. Most metropolitan areas are situated along or with access to the Atlantic Coast. With some exceptions the interior is rural with numerous small towns and villages.

Precipitation is the ultimate source of all the freshwater available for use, although water stored in deeper aquifers may have been emplaced many thousands of years ago. Annual precipitation of the region averages nearly 40 inches but varies somewhat depending on location. It is about 40 inches or more along the coast and over 50 inches in upstate New York, southern Vermont and West Virginia. The amount is slightly less than 36 inches in northern Vermont, south Central New York, south central Pennsylvania, and near the Virginia-West Virginia border. Average annual temperature ranges from about 44°F. (6.6°C.) in northern Vermont to about 60°F. (15°C.) in southern Virginia.

As of 1975, 54 percent of the total area in the region was forested (mixed hardwoods and oak-hickory type); 28 percent was used for croplands, pasture and other agricultural uses; 7 percent was urban, 3 percent was water surface; and 8 percent was in miscellaneous use. By the year 2000, it is estimated that the amount of land used for urban purposes will increase by 23 percent while cropland will decrease about 5 percent.

The major topographic features are the result of marked difference in geological processes over millions of years. Among these are 1) compression and uplifting of the earth's crust forming the Appalachian Mountains; 2) glacial erosion and deposition as far south as Pennsylvania and Long Island leaving a mantle of till in the uplands and stratified drift in lowlands; and 3) accumulation of materials from uplifted rocks forming a seaward thickening wedge of mostly unconsolidated sedimentary rocks (the Coastal Plains). Rock types are highly varied. The mountainous areas are underlain by crystalline igneous and metamorphic rocks (granite, schist, gneiss, slate, quartzite and marble), largely Precambrian in age. Highly folded and faulted Paleozoic limestones, sandstones and shales underlie the Valley and Ridge Province. The Coastal Plain includes about 25,000 of the 108,000 total square miles and is composed of low relief sands and clays that dip gently seaward and serve as excellent sources for large quantities of ground water.

The highly varied nature of the lithology leads to great differences in ground water production. The surficial deposits of the Coast Plain are highly permeable unconsolidated sand and gravel that produce large quantities of water from wells less than 300 feet in depth; yields may be as high as 20,000 gpm.

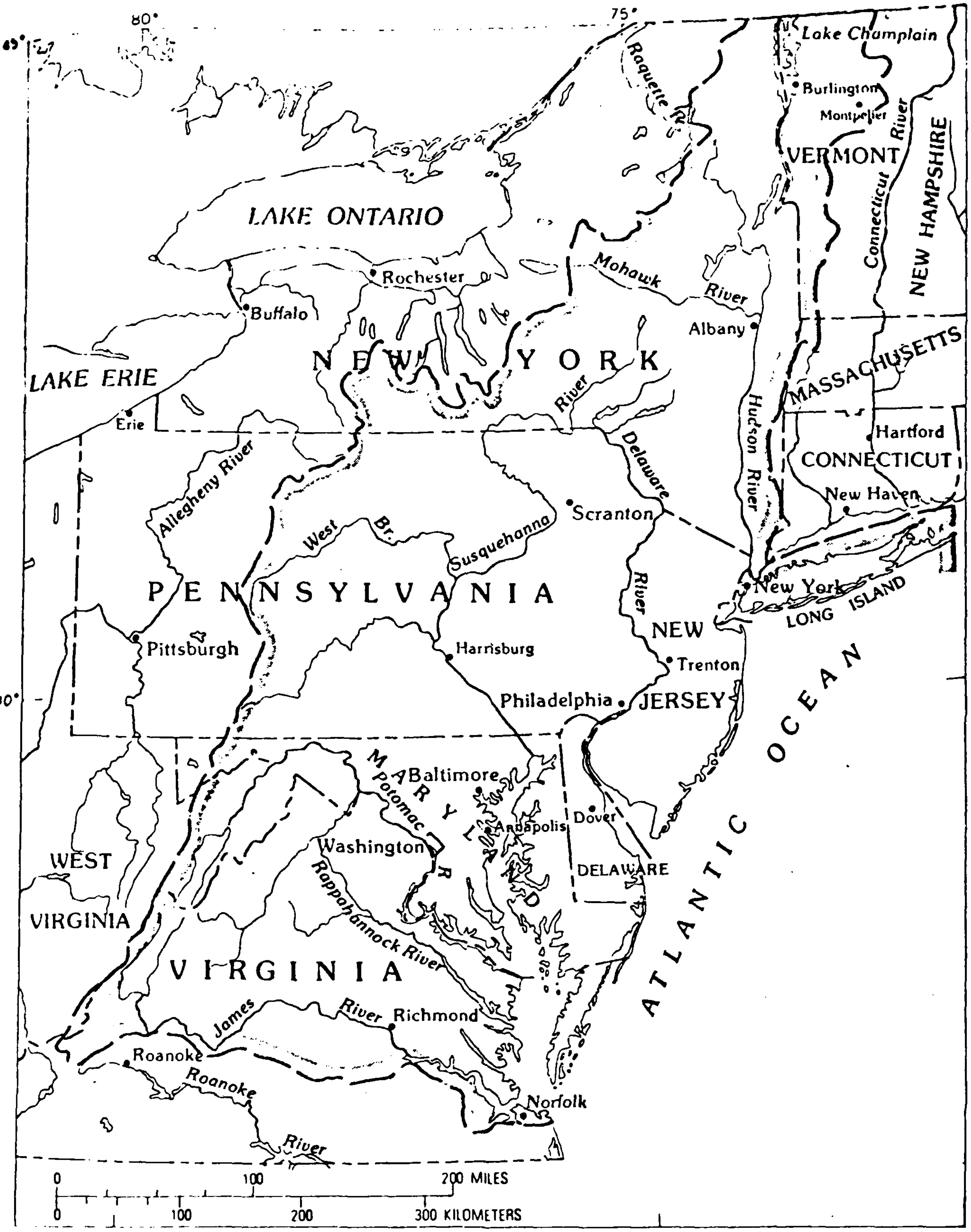


Figure 28. Location and drainage of the Mid-Atlantic Region.

Underlying the unconsolidated deposits are deeper artesian aquifers that are highly productive. In areas underlain by weathered crystalline metamorphic and igneous rocks, well yields are small to moderate (15 to 400 gpm). In some areas (the Valley and Ridge Province), limestones interlaced by caverns produce large quantities of water. Glacial outwash deposits and watercourse aquifers are the chief sources of ground water supplies in the glaciated areas of the region.

In the Coastal Plain Province, baseflow (ground water) ranges from about 40 to 95 percent of streamflow, and from 25 to 90 percent in the part of the region underlain by consolidated rocks. The average potential yield of ground water from the entire Mid-Atlantic Region under present hydrologic conditions is estimated to be at least 38.6 bgd or 43.2 maf per year. As of 1975, total withdrawals from ground water were only 2.7 bgd (3.0 maf). In addition to this estimated quantity of ground water available for use, at least another 140 to 350 trillion gallons (430-1072 maf) of water are estimated to be in storage in the major unconfined shallow aquifers.

The estimated average annual runoff from this region is 81.0 bgd (90.7 maf). The mean annual streamflow is estimated to be 79.2 bgd (88.7 maf). Thus, consumptive use, evaporation and deep percolation account for about 2.0 maf per year, a relatively small part of the total annual runoff. The distribution of the streamflow does not appear to be greatly skewed as the median is 77.8 bgd (87.1 maf), only slightly less than the mean indicating no great disparity between the amount of time that low flows and high flows occur. However, there is an apparent tendency for persistent occurrence of low flows for the Potomac River near Washington, D. C. as during 1930, 1965, and 1966 (Figure 29). The 5 percent exceedence value is 115.1 bgd (128.9 maf) and the 95 percent exceedence is 48.4 bgd (52.2 maf); Q_{05}/Q_{95} is 2.4 indicating the streamflow is not highly variable. In the northern part of the region, maximum monthly flow occurs in April and during March, April and May for the central section. In the southern part, maximum flow occurs in March although that in April is nearly as great. The gaging stations analyzed for six subregions within the region cover the periods 1900-77, 1913-77, 1932-77, and 1930-77; none of these show any significant trends in their flow records.

Reservoir storage is not particulary large in this region; 6,200 bg (19.0 maf) is the normal storage for purposes other than flood control and 7,850 bf (24.1 maf) over normal is designated for flood control. Flood damages (total for urban, agricultural and other sources) totaled 183 million dollars in 1975. Assuming no climatic change, an increase to 296 million dollars is estimated by the year 2000. This 62 percent increase is based on a projected increase in population that will require an additional 5.8 million acreas, an increase of 32 percent.

Using the techniques outline earlier, climatic records from Washington, D. C., Philadelphia and New York have been used to analyze changes in runoff for the region for the 4 climatic scenarios. The ratio of the mean annual runoff to the present runoff is shown in Table 4 for each scenario. The net effect of scenario 1 (warmer and drier) is to reduce the runoff under the present climate by about 35 percent (or to 65 percent of the present). In contrast, scenario 2 (cooler and wetter) would increase the present runoff by about 1.40 times. Scenario 3 (warmer and wetter) would increase runoff

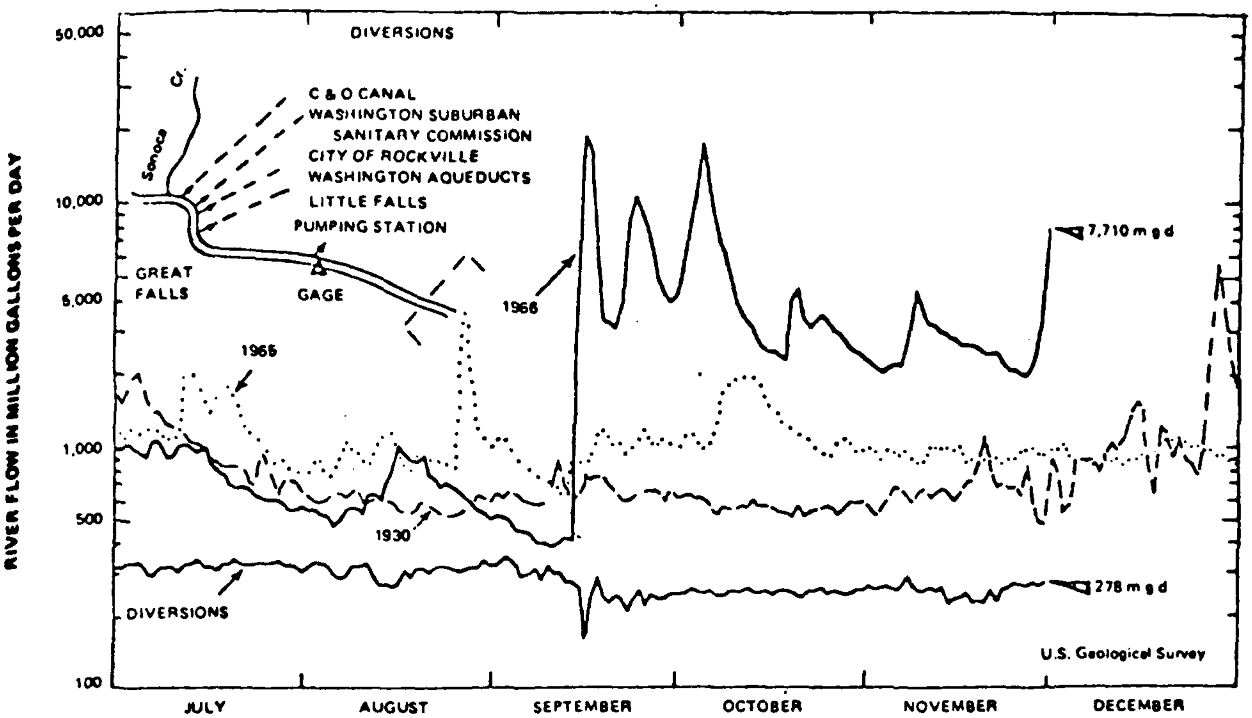


Figure 29. Rates of flow in the Potomac River near Washington, D. C. for 1930, 1965 and 1966. Flow includes that diverted for supplying the Washington metropolitan area plus that measured at the gage (from Beltzner, Klaus (editor) 1976. Living with Climatic Change).

$\overline{Q}$ scenario/$\overline{Q}$ present

Scenario	South	Central	North	Average
1 (warmer and drier)	.66	.66	.66	.66
2 (cooler and wetter)	1.50	1.37	1.40	1.42
3 (warmer and wetter)	1.07	1.17	1.13	1.12
4 (cooler and drier)	.87	.93	.90	.90

Table 4. Ratio of projected mean annual runoff to present runoff in the Mid-Atlantic Region for each of 4 climatic scenarios.

1.10 times, and scenario 4 (cooler and drier) by about 0.90 times.

Although the postulated effects of scenarios 3 and 4 probably affect local water resource management, the results would probably be trivial for the region as a whole. Scenario 1 (warmer and drier) would result in decreased runoff of about 66 percent of the present or roughly 53.1 bgd (59.5 maf) as compared to the present 80.5 bgd (90.2 maf), which is well above the present withdrawal of 18.3 bgd (20.5 maf) of fresh water in the region. Presumably however, this scenario would result in extended low flow periods at least comparable to those of 1930 and 1965-66, but the large unused ground water reserve should be a developable source during such periods. Water shortages would probably be restricted to local situations and based on projections through the year 2000 should not be a region wide problem. Thermal and industrial waste pollution problems would be of major concern for the whole region.

The occurrence of scenario 2 (cooler and wetter) would pose the most difficult water management problems. An increase of 1.4 times the present runoff would likely inundate many low lands and flood plains. With the projected increase in urban land use, flood damage could greatly increase unless remedial control measures were implemented. The colder temperatures would result in much more ice on rivers and estuaries resulting in navigation and shipping problems, and perhaps aggravated spring flooding associated with the breakup of ice.

The postulated effects on the overall system are outlined in the speculation impact matrices, Tables 3 and 4 in the Appendix.

REGION 03 - SOUTH ATLANTIC-GULF REGION

The South Atlantic Region encompasses 173.6 million acres of which 6.8 million acres represents water surface. It includes all of South Carolina and Florida plus parts of Virginia, North Carolina, Georgia, Alabama, Mississippi and Louisiana (Figure 30). There are 24 major and numerous minor river systems within the region along with 1945 miles of ocean front and 11,847 miles of bay and estuary shoreline. The region begins on the eastern slope of the Blue Ridge Mountains and is mostly situated in the Blue Ridge, Piedmont and Coastal Plains Provinces. Topography varies considerably from the rugged mountains with conspicuous relief and narrowly confined valleys, through the rolling Piedmont to flat, poorly drained lands in the Lower Coastal Plain.

Climate is generally characterized by mild winters and warm-to-hot summers. Precipitation is well-distributed throughout the year. Average annual rainfall ranges from a low of 40 inches at Key West, Florida to a high of 80 inches in the southern part of the Blue Ridge Mountains. The region averages about 50 inches as compared with the 30-inch national average. The distribution of rainfall is more variable in southern Florida than in other parts of the region. January temperatures range from an average of 30°F. in the mountains to 70°F. in south Florida. Average July maxima are about 80°F. in the mountains to 94°F. in central Georgia. Temperatures rarely exceed 100°F. or fall below 0°F.

Natural vegetation reflects the abundant precipitation and mild temperatures. Mixed hardwoods are dominant in the mountains while large acreages of southern pine forests occur in the Piedmont and Coastal Plain. Stands of bottomland hardwoods are common along watercourses in the Coastal Plain while sub-tropical to tropical vegetation is native to south Florida.

Forests cover 61 percent of the area; agricultural uses amount to 25 percent; urban uses, 3 percent; water surface, 4 percent, and other uses, 7 percent. Total land devoted to agriculture is expected to increase slightly by the year 2000; harvested croplands are expected to increase about 36 percent. Irrigation will increase rapidly in some farming areas, this in spite of the usually abundant rainfall. The additional land for agriculture will come from forest clearing and land drainage.

The South Atlantic-Gulf Region includes parts of five physiographic provinces. Each has distinctive features of ground water occurrence related to the character of the underlying rocks. These provinces include the Piedmont, which overlies crystalline rocks and encompasses about one-fourth of the region; the Valley and Ridge, overlying strongly faulted carbonate rocks; the Appalachian Plateau with overlying horizontal coal-bearing sandstone rock; the Blue Ridge; and the Coastal Plain, composed of sediments and covering almost three-fourths of the region. The Coastal Plain Province contains the region's largest ground water resources and represents some of the most productive aquifers in the country.

In the Piedmont and mountain sections, fractures in the crystalline bedrock form the principal aquifers. The overlying weathered material

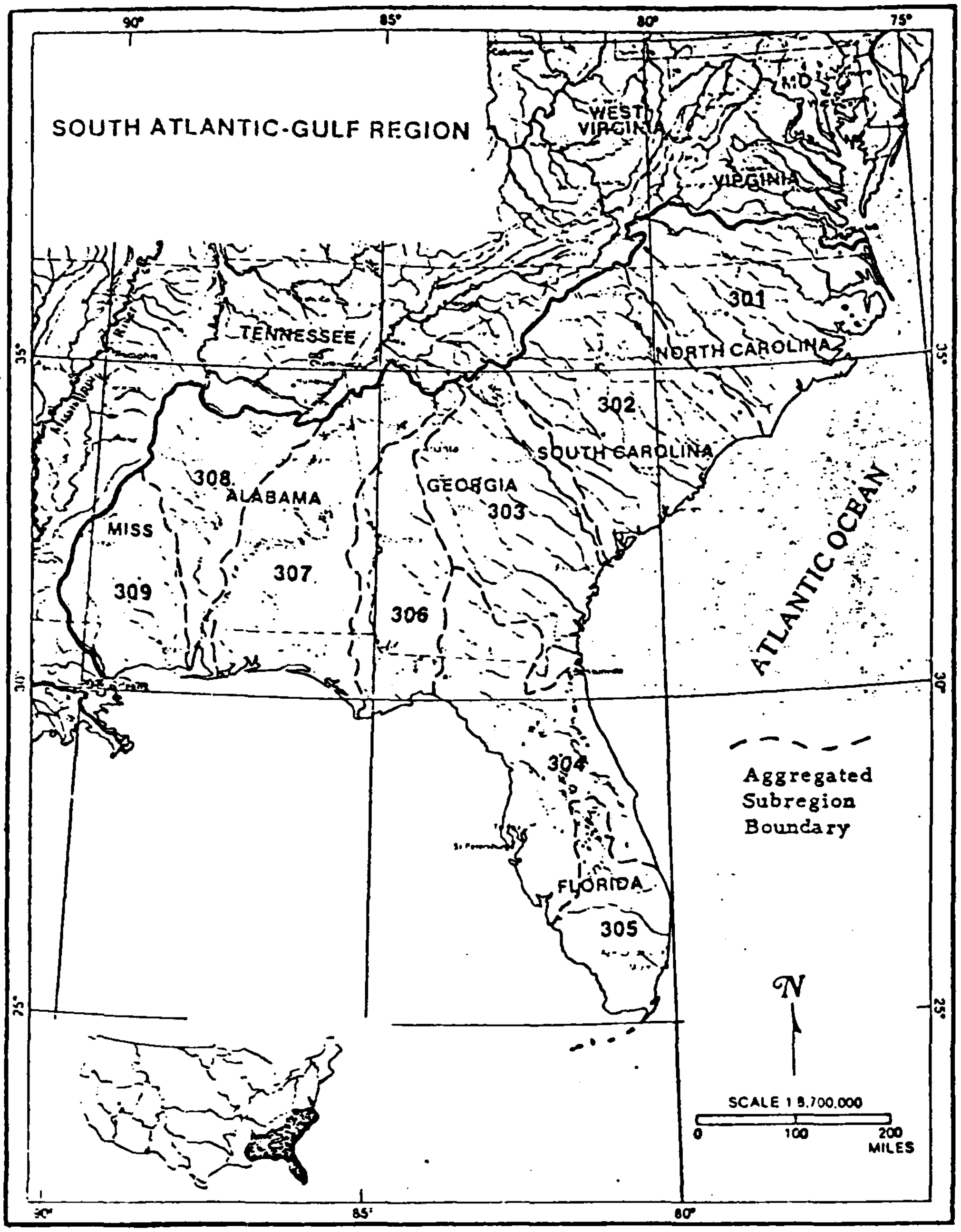


Figure 30. Location and drainage of the South-Atlantic Gulf Region.

(saprolite) varies in thickness from a few feet on slopes to more than 100 feet in valleys and constitutes a significant storage area. Yields from the bedrock-fracture aquifers are generally low, averaging less than 50 gpm. In general, however, the ground water potential for these areas has been underrated.

In the Valley Ridge Province ground water occurs in fractures and solution openings in the carbonate bedrock. Highly productive, cavernous limestone characterize the ground water hydrology. Numerous springs supply municipal and industrial needs in the area and locally; wells may produce more than 1000 gpm.

There is great potential for ground water development in the Coastal Plains Province. This province occupies almost three-fourths of the region and contains some of the most productive aquifers in the United States. The chief aquifers are 1) sands and gravel extending in a broad arc from northeastern Mississippi to southern Virginia; and 2) highly productive limestone and dolomite areas throughout Florida and Georgia as well as coastal South Carolina and North Carolina. Large springs are numerous, with yields up to millions of gallons per day. Locally, wells may yield as much as 20,000 gpm from carbonate rocks and 5000 gpm from sand and gravel aquifers.

Present ground water withdrawals within the region are 5.5 bgd (6.16 maf) and 0.3 bgd of this amount is in excess of recharge. This recharge deficit is related to very heavy pumpage in some of the more heavily populated and industrialized areas and is a local rather than region-wide problem. The amount that can be feasibly withdrawn from storage is estimated at 13,680 maf, the largest of any region in the United States.

The South Atlantic-Gulf Region is one of the water rich areas of the conterminous United States. Average annual runoff is estimated at 332.5 bgd (372.4 maf) and about 0.34 bgd (0.38 maf) is mined from ground water. Total annual consumption is 4.87 bgd (5.45 maf) and the remaining streamflow is 228 bgd (225.4 maf). The amount needed for optimal fish and wildlife habitat is estimated at 180.6 bgd (202.3 maf).

The median annual streamflow is 219.2 bgd (245.5 maf) indicating a slight skewness in the distribution with low flows predominating. The 5 percent exceedance flow is 356.6 bgd (399.4 maf) and the 95 percent value is 121.8 bgd (136.4 maf); Q_{05}/Q_{95} is 2.9.

Total withdrawals in 1975 were 24.51 bgd (27.5 maf) and this is expected to increase to 28.34 bgd (31.7 maf) by the year 2000. Normal reservoir capacity in the region is 13,382 bg (41.1 maf) and the flood control storage is 19,799 bg (60.7 maf).

Although the monthly variation in streamflow changes within the region, the seasons of high and low flows are the same except for the Florida Peninsula. The period of peak flow is in February, March and April; low flows occur in June, July and August. In general the individual monthly flows are moderately skewed with low flows predominating.

Two peak seasons occur in the upper Florida Peninsula, March-April and

August, September and October; low flows occur in May and June. The monthly distributions are only slightly skewed. High flows in the lower peninsula occur during July-September and low flows during December-May. The monthly values are highly skewed with low or no-flows predominant.

Except for one sub-region, there are no significant trends in flow. The exception, located in North Carolina, shows a significant upward trend of 0.678 percent per year for the period 1930-1977. It is doubtful that this trend is related to climatic change since it is not evident in adjacent sub-regions.

Local flooding is a problem throughout the region. Tropical storms moving inland or along the coast cause torrential downpours during late summer and early fall. During other parts of the year, intense thunderstorms of short duration or extended periods of rainfall may cause streams to overflow and cause flood damage.

Total fresh water withdrawals from all sources averages 24.5 bgd (27.4 maf) in 1975. Uses included steam-electric power generation, 52 percent; irrigation, 14 percent; manufacturing, 17 percent; and central and non-central uses, nine percent. Withdrawals are expected to increase to 28.3 bgd (31.7 maf) by the year 2000. Consumption of fresh water is expected to increase from 4.9 bgd (5.5 maf) in 1975 to 10.1 bgd (11.3 maf) in 2000. Except in local situations, there is ample water, both surface and underground, to meet these projected needs.

Precipitation and temperature data from Montgomery, Alabama, Charleston, South Carolina and Raleigh, North Carolina were used to develop projections under the four climatic change scenarios. The $\bar{Q}$ scenario to $\bar{Q}$ present ratios for mean annual flow is shown in Table 5.

Scenario	Southwest	Central	Northwest	Average
1 (warmer and drier)	.71	.57	.65	.64
2 (cooler and wetter)	1.45	1.46	1.46	1.46
3 (warmer and wetter)	1.10	1.07	1.09	1.09
4 (cooler and drier)	.94	.87	.89	.90

Table 5. Estimated Ratios of $\bar{Q}$ scenario to $\bar{Q}$ present for Mean Annual Flows in the South Atlantic-Gulf Region.

A scenario 1 (warmer and drier) situation would result in a decrease in runoff to about 0.65 of the present value. This reduction to 216 bgd

(242 maf) would not cause serious problems because of the large water supply within the region. Local shortages, especially in areas with very heavy usage and demands, would likely occur possibly resulting in salt water encroachment.

Under scenario 2 (cooler and wetter) mean annual runoff would be 1.45 times greater than present or 482 bgd (540 maf). Flooding would increase and low-lying areas would be subject to periodic inundation. Additional flood control (reservoirs) would be necessary.

REGION 04 - GREAT LAKES

The Great Lakes Region (Figure 31) encompasses a drainage area of about 134,000 square miles, including 3947 square miles of water area. The basin includes portions of Illinois, Indiana, Michigan, Minnesota, New York, Ohio, Pennsylvania and Wisconsin. Although the region comprises only 4 percent of the land area in the conterminous United States, it supports 14 percent of the population and contributes a much larger percentage of the nation's economic activities.

Precipitation varies from 28 inches annually in the northwest corner of the region, near Duluth, to over 50 inches in the extreme eastern part in the Adirondacks. Annual precipitation over the region averages 31 inches, but areas east of the lakes generally receive more precipiation than upwind areas. Precipitation is fairly evenly distributed throughout the year with February having the least (1.78 inches) and September the most (3.24 inches).

A large part of the precipitation is lost to evaporation with mean annual lake evaporation ranging from 24 to 32 inches over the region. About 80 percent of the evaporation occurs during the May-October period.

The region has a unique combination of agricultural and forest land, minerals and water resources. Almost half of the land area is forested, much of which has been reforested by natural regeneration and planting. Agricultural uses occupy 40 percent of the land followed by urban and built up areas, 5 percent, and miscellaneous uses, 8 percent. Urban land is expected to increase about 30 percent by the year 2000. Irrigated land will expand from the present 164,000 acres to nearly 335,000 during the same period. About one million acres will likely be added to agricultural uses by land planning.

The Great Lakes Region lies principally within two major physiographic provinces, the Superior Upland and the Central Lowland. The Upland areas consist of a glaciated peneplain developed in crystalline rock whereas the Lowland is a lacustrine plain.

The bedrock succession consists of sedimentary formations overlying a basement of Precambrian igneous and metamorphic rock. These basement rocks are expressed as uplands extending from Minnesota, easterly along the northern edge of the region into the Adirondack Mountains. Major structural features include a deep sedimentary basin centered under Michigan, a shallow sedimentary plain bordering the Appalachian trough in the Lake Erie-Ontario area and a basement rock high extending between the Michigan basin and the Appalachian trough.

Ground water resources are extensively used in many of the urban areas resulting in some mining, especially around Chicago and parts of Indiana. Present ground water withdrawals are 1.2 bgd (1.3 maf) and are not anticipated to significantly increase in the future.

Unconsolidated glacial outwash sand and gravel deposits are highly permeable and represent the best aquifers in the region. The most productive

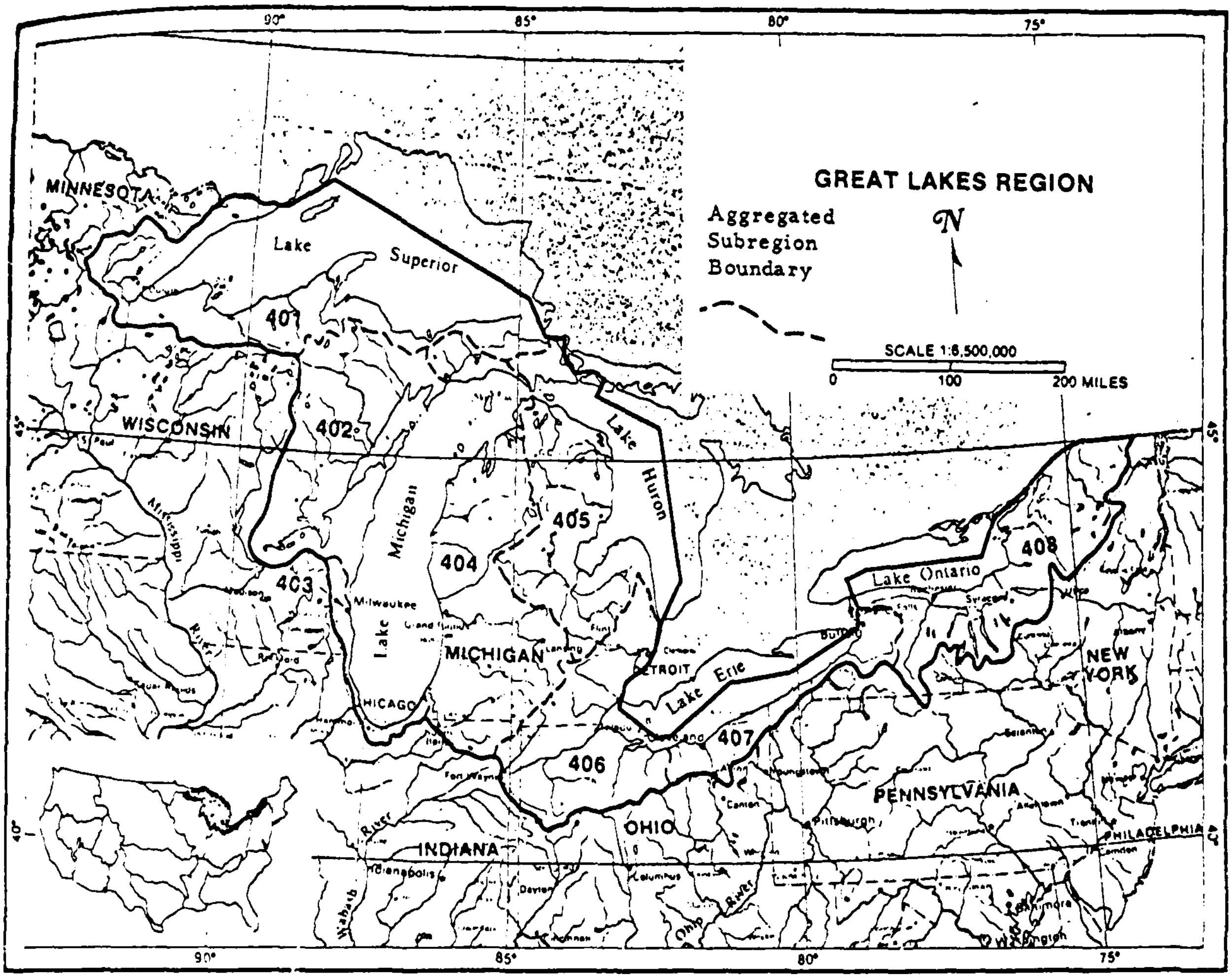


Figure 31. Location and drainage of the Great Lakes Region

deposits are in the valleys of major streams with recharge being induced by infiltration of streamflow in many areas. Yields as high as 5000 gpm are obtainable from wells in some thick deposits of sand and gravel.

Limestone and dolomite constitute the most common bedrock aquifers in the region with well yields as high as 1000 gpm where they are overlain by unconsolidated deposits. These occur along the northern and eastern shores of Lake Michigan and along the southern shore of Lake Ontario. A thick sequence of sandstone with well yields as high as 1300 gpm, is present along the western and northern part of the Lake Michigan basin. In this region, most recharge results from snowmelt and rainfall infiltrating to the water table. However, highest well yields are obtained from aquifers with direct hydraulic continuity to lakes or streams. Heavy pumping tends to induce recharge from these surface water bodies. Baseflow maintains streamflow during dry periods and helps to maintain lake levels and wetlands. Although variable with season, the baseflow is estimated to be nearly 26 bfd (29.1 maf) for the region.

Total annual runoff within the entire basin is estimated at 75.26 bgd (84.3 maf). In 1975, approximately 0.03 bgd (0.034 maf) of the supply was obtained by mining ground water and 0.02 bgd (1022 maf) was imported. Water consumed within the region amounted to 2.6 bgd (2.91 maf) but is expected to rise by the year 2000, total withdrawals are anticipated to decline to roughly 25.6 bfd (28.7 maf). This is based on the assumption of major increases in industrial recycling and reuse of water.

Presently, the median annual flow is 77.8 bgd (87.14 maf) which is only slightly less than the mean indicating little to no significant skewness in the flow regime. The variability is not marked as the 95 percent exceedence flow is 44.9 bgd (50.3 maf) and the 5 percent is 103.9 (116.4 maf). Q_{05}/Q_{95} is 2.3. Total surface outflow from the region in and average year is estimated to be near 73 bgd (81.76 maf). This represents only the flow from the U.S. and does not include inputs from the Canadian portion. This flow, shown schematically in Figure 32, is fairly constant in both wet and dry years.

The monthly distribution of flows varies across the basin. Extremely low flows in certain streams occur during midwinter (January and February) and summer (July, August, and September) due to low precipitation and low baseflow. High peak flow generally occur during the spring months of March, April and May. In almost all subregions (Figure 31) the distribution of the monthly flows are somewhat skewed but in subregions 403, 406, and 407 they are highly skewed and highly variable especially during the winter and spring months (November-May). Periods of record analyzed are from 1899-1977 (subregion 406) to 1936-1977 (subregion 405). Only subregion 405 showed a significant trend, an increase of 0.75 percent/year for the period 1936-1937. This may be related to the record length but could represent a climatic anomaly perhaps resulting from inadvertant weather modification due to industrialization.

Flooding is a problem throughout the Great Lakes Region affecting both urban and agricultural areas. In 1975, flooding damages were estimated at 105 million dollars (1975) and they are expected to rise to near 135 million dollars (1975) due to an increased development of flood prone areas.

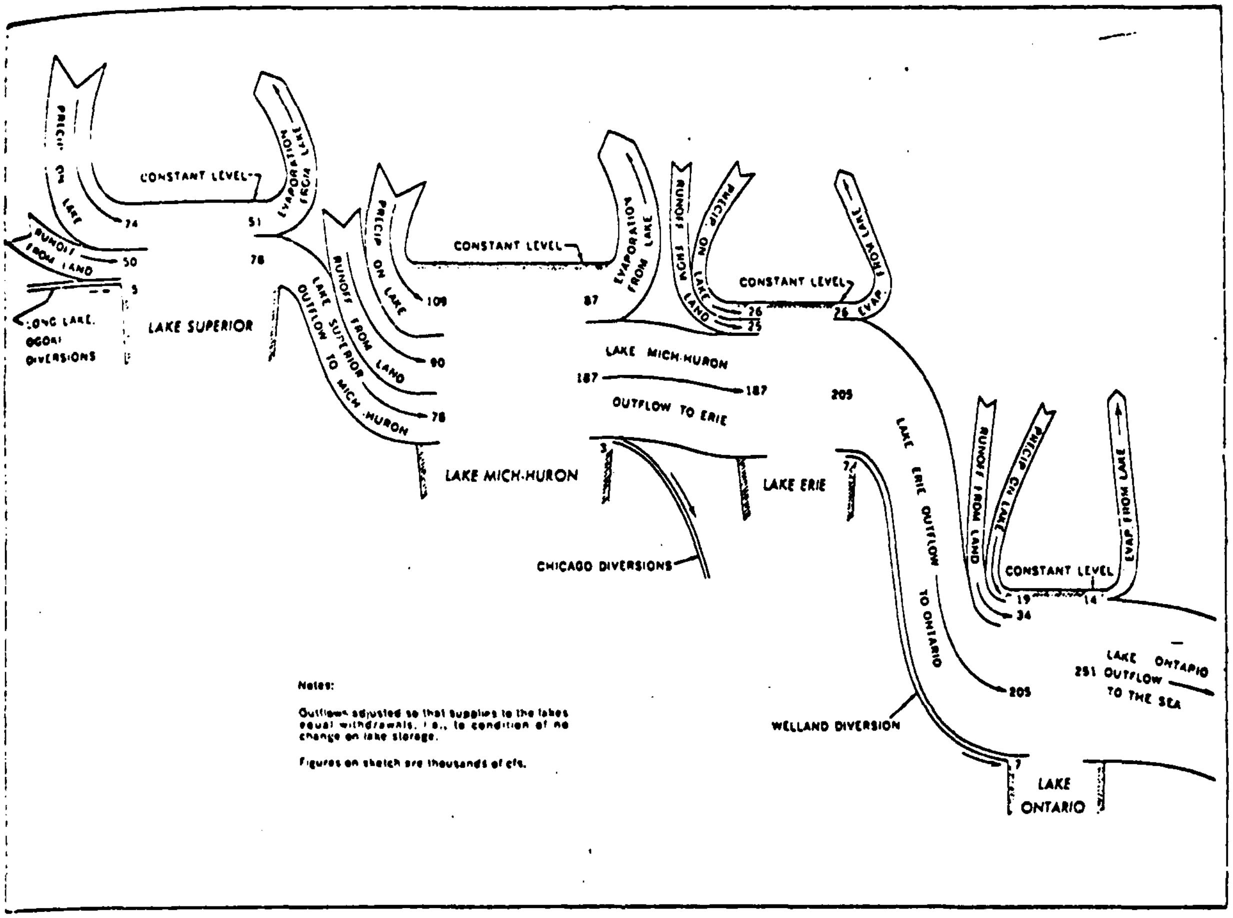


Figure 32. Annual water balance of the Great Lakes system (figures are in thousand of cubic feet per second).

Flooding problems are caused principally by two major factors; they are storm surges on the Lakes themselves, especially during high lake level periods, and high intensity storms over the land areas. Present reservoir storage for flood waters is 4200 bg (12.33 maf) and that for other purposes is 3300 bg (19.12 maf).

The ratio of $\overline{Q}$ scenario/$\overline{Q}$ present for the west, central and east parts of the region are shown in Table 6. Precipitation and temperature stations used in the estimation procedure include Chicago, Sault Ste. Marie, Ontario (Canada), and Buffalo.

Scenario	South	North	East	Average
1 (warmer and drier)	.64	.64	.73	.67
2 (cooler and wetter)	1.36	1.21	1.55	1.37
3 (warmer and wetter)	1.14	.92	1.14	1.07
4 (cooler and drier)	.86	.83	1.05	.91

Table 6. Ratio of $\overline{Q}$ scenario/$\overline{Q}$ present for Great Lakes Region.

Under conditions of scenario 1 (warmer and drier), the present annual runoff would be reduced by 33 percent, resulting in a mean annual runoff of 50.4 bgd (56.4 maf). This is still above the present withdrawal rate of 43 bgd (48.2 maf) and well above the projected 35.6 bgd (28.7 maf) by the year 2000. Some increase in conjunctive use of ground water may be necessary. Scenario 2 (cooler and wetter) is postulated to increase mear annual flow by 1.37 times, producing a mean annual flow of 103 bgd (115.4 maf). This would probably result in increased lake levels along with large scale flooding and inundation of lowlands and urban areas along the shorelines. Additional flood prevention would be necessary and improved surface water quality would result. Scenarios 3 and 4 remain trivial. Speculative impact effects are shown in Tables 7 and 8 in the Appendix.

REGION 05 - OHIO REGION

The Ohio Region includes the surface water drainage boundaries of the Ohio River Basin, exclusive of the Tennessee River System. The region comprises 163,000 square miles and is bounded on the north by the Great Lakes drainage; on the east by the divide of the Appalachian Mountains; on the south by the Tennessee River Basin; and on the west by tributary drainages of the upper Mississippi River (Figure 33).

Annual precipitation is rather high, averaging from 36 to 56 inches; the predominant range is 40 to 46 inches. Mean annual temperatures vary in north-south direction, ranging from 50°F. along the northern boundary to 60°F. in the southern part of the region.

Agriculture is the principal land use on 49 percent of the area (cropland, 35 percent; pasture, 14 percent). About 42 percent of the land is forested while urban areas occupy 3.3 percent; and miscellaneous uses account for about 5.5 percent. Major land use changes are expected by the year 2000. A reduction of about one million acres is expected in forest land accompanied by an equal increase in urband and built-up areas.

The highly variable topography and geology of the region is illustrated by the occurrence of four major physiographic provinces within the area. These include the Valley and Ridge Province; the Appalachian Plateau; the Interior Low Plateau; and the Central Lowland. Alluvium, outwash and glaciofluvial deposits constitute the most productive aquifers in the region and include the following:

1. Holocene alluvium - these silt, sand and gravel deposits are present along the lower reaches of the major tributary valleys south of the Ohio River.

2. Outwash - Sand and gravel deposits that are extensive in the valleys of the major tributaries within the limits of glaciation (the area north and west of the Ohio River). These deposits are an excellent source of ground water.

3. Glaciofluvial deposits - these are a mixture of outwash and alluvium that occur along many of the major tributaries and in the Ohio River Valley.

4. Glacial till - the principal glacial deposit in the area. It is a heterogeneous mixture of clay, silt, sand and gravel that has very low hydraulic conductivity and consequently is a poor aquifer.

The region is underlain by a series of bedrock units of variable thickness and hydrologic character with ages ranging from Tertiary to Precambrian. Structurally, the region is dominated by two basins, the Illinois in the west and the Appalachian to the east. The basins are largely separated by the Cincinnati Arch. The slope on the surface of the basement complex from the arch toward both the Appalachian and Illinois basins is the central feature and controls the dip of the younger sedimentary rocks overlying the basement.

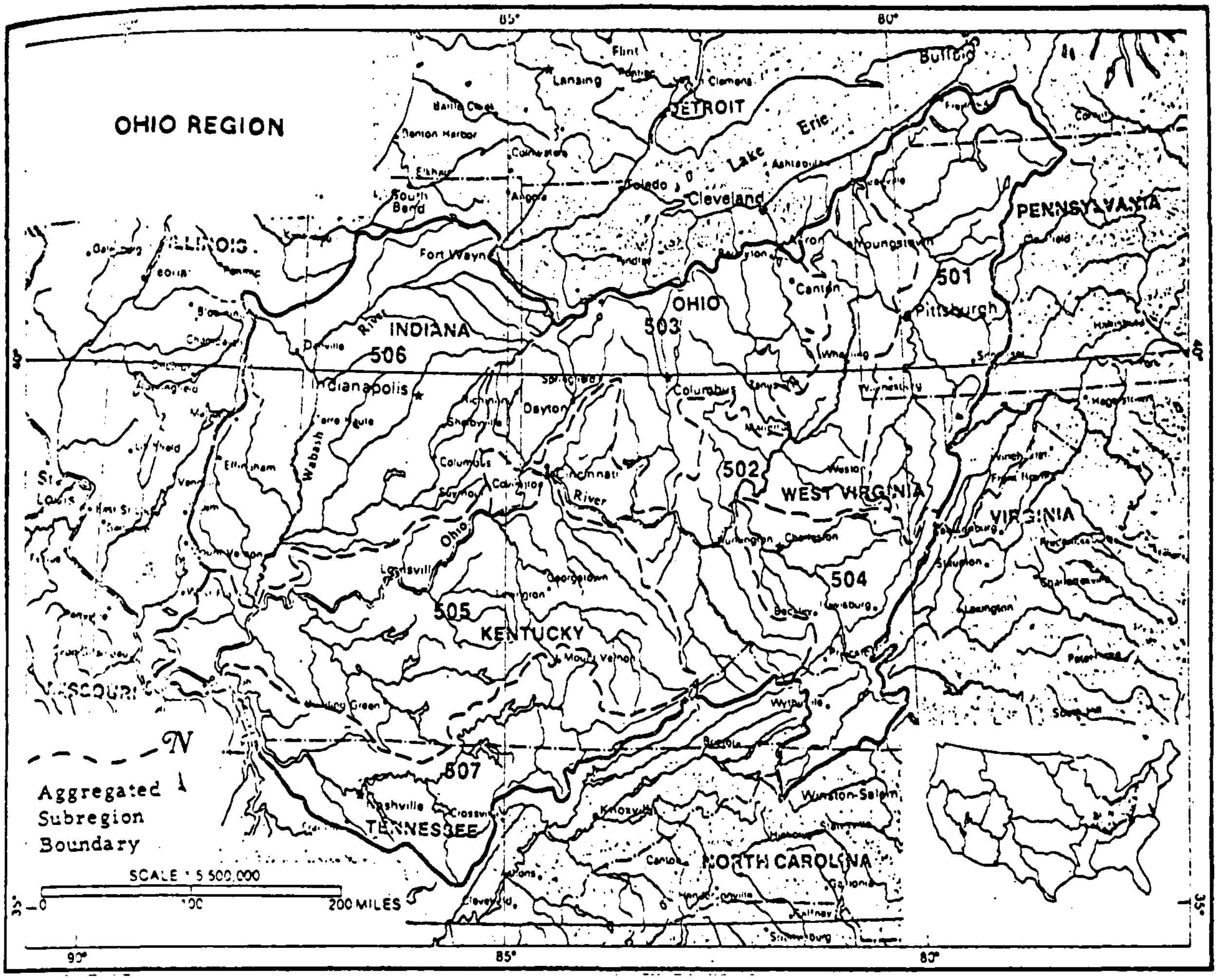


Figure 33. Location and drainage of the Ohio Region

In general, the bedrock aquifers are not highly productive. The most productive wells are those situated adjacent to major streams and designed to induce flow from the stream to the alluvial ground water reservoir. Baseflow contributions to streamflow are estimated to be about 60 percent flow duration level.

Mean annual streamflow from the region is estimated to be 180.1 bgd (201.7 maf). Mean and median flow is 178.0 bgd (199.4 maf) with the 95 percent exceedence level being 254.0 bgd (284.5 maf) and the 5 percent level 105.0 bgd (117.6 maf); Q_{05}/Q_{95} is 2.4. However, 40.8 bgd (45.7 maf) is stream inflow (from outside the region) so that about 140.0 bgd (156.8 maf) is generated within the region.

Regional water consumption is nearly 1.8 bgd (2.02 maf) and this is expected to increase to 4.3 bgd (4.8 maf) by the year 2000. Manufacturing and steam-electric plants account for over 63 percent of the 1975 water consumption. A major increase in consumption by the steam-electric sector is expected by the year 2000, reaching a predicted use of 1.4 bgd (1.6 maf) and representing 39 percent of the total consumption.

Total withdrawals in 1975 amounted to 34.9 bgd (39.1 maf) with steam-electric accounting for 60.2 percent, manufacturing 31.1 percent, domestic 5.3 percent and the remainder divided between irrigation, minerals and miscellaneous uses. Annual withdrawals are expected to decrease to 16.9 bgd (18.9 maf) by the year 2000 with the greatest decline in use for manufacturing. Domestic uses will more than double and will account for 13.8 percent of the total.

The monthly distribution of streamflow varies over the 7 sub-regions (see Figure 33 for sub-regions). In the northeastern sub-region (501) the maximum flow occurs in March and there is considerable difference between this and the low flow months of July, August, September and October. Within month variability is high for all except the low flow months. All other sub-regions are similar except for number 507 which borders the Tennesse River System. Two peak flows occur in this sub-region, February and May, and within month variation is great for all months. This sub-region does show a significant upward trend of 1.39 percent per year for the period 1940-1977. Although this period conforms to the recent cooling trend, the increase is most likely related to changes in land use as adjacent areas do not show similar changes.

About 50 percent of the streamflow occurs in the four months of January to April; lowest amounts generally occur in September and October. Total annual runoff amounts to about 17.3 inches over the entire watershed.

Precipitation and temperature data from Nashville, Tennessee, Cincinnati, Ohio and Pittsburg, Pennsylvania were used to predict runoff changes for each of the four climatic scenarios. The ratios of the changes are shown in Table 7.

Under scenario 1 (warmer and drier) the present streamflow would be reduced an estimated 62 percent. Thus the mean annual streamflow, exclusive of inflow, would become 86.8 bgd (97.2 maf). With present withdrawals of 34.9 bgd (39.1 maf) and an expected decrease by the year 2000, no general water shortages would likely occur. Local shortages, along with navigation problems on the Ohio

River, due to extended periods of low flow, would be anticipated.

Scenario	South	Central	North	Average
1 (warmer and drier)	.67	.60	.60	.62
2 (cooler and wetter)	1.40	1.45	1.45	1.43
3 (warmer and wetter)	1.10	1.10	1.05	1.08
4 (cooler and drier)	.87	.85	.85	.86

Table 7. Ratio of $\overline{Q}$ scenario to $\overline{Q}$ present for Annual Flows in the Ohio Region.

Scenario 2 (cooler and wetter) conditions would increase the present mean runoff 1.43 times resulting in a mean annual flow of 200 bgd (224 maf). Increased flooding along the Ohio River and its tributaries would likely cause considerable damage to bottomland agriculture. Ground water levels would rise and probably create problems with basement flooding, along with failures of water and sewage distribution systems in cities and towns located on or near flood plains. Changes related to scenarios 3 and 4 would probably be trivial. The probably effects of scenarios 1 and 2 are shown in the speculative impact matrices, Tables 9 and 10 in the Appendix.

REGION 06 - TENNESSEE REGION

The Tennessee Region is composed of 41,000 square miles dominated by the Tennessee River System. It includes parts of Alabama, Georgia, Kentucky, Mississippi, North Caroling, Tennessee and Virginia (Figure 34). About 1,054 square miles of the area is water surface.

Precipitation varies considerably over the region because of the highly varible topography. Some of the most rugged terrain in the eastern United States is located in the eastern half of the region. In contrast, the western portion is characterized by low rolling hills. Altitudes range from 6,684 feet at Mt. Mitchell, North Carolina to 302 feet at the mouth of the Tennessee River near Paducah, Kentucky. Precipitation ranges from 45 inches in the northwest corner to as much as 85 inches in the mountainous southeast. The area-wide average is about 52 inches. Temperatures are moderate, ranging from about 60°F. to 50°F. from the southwestern to the northeastern boundaries.

Nearly 53 percent of the region is forested (mixed hardwoods) with the eastern half having the heaviest concentrations of wooded areas. Harvested croplands cover about 10 percent with pasture and other agricultural uses occupying 22 percent of the area. Urban uses account for 2.3 percent. Only small changes in land use are expected by the year 2000.

The major types of aquifers in the region are unconsolidated deposits (sand and gravel), carbonate rocks and fractional noncarbonate rocks. One or more of these aquifers occur in each of the six physiographic subdivisions of the region. The unconsolidated sand aquifers are both the most homogeneous and productive with wells commonly yielding 200-600 gpm. In the carbonate rocks, water occurs in solution openings and consequently is not uniformly distributed. Location, depth and yield of water in these aquifers is difficult to predict but yields up to 300 gpm are not uncommon. Yields from the fractional carbonate rocks are low.

About one-fifth to one-fourth of the precipitation falling on the region is recharge to the groundwater reservoirs. Base flow to the streams is about 22.0 bgd (24.5 maf) or about 55 percent of the total runoff.

The annual runoff generated within the region is 41.1 bgd (46.0 maf). Total consumption is 0.31 bgd (0.35 maf) leaving a stream outflow of 40.8 bgd (45.7 maf). The median of annual flows is equal to the mean (40.8 bgd) whereas the 5 percent exceedence value is 57.9 bgd (64.8 maf) and the 95 percent exceedence is 31.4 bgd (35.2 maf); Q_{05}/Q_{95} is 1.8. These statistics suggest that the flow from the region is not highly variable, and the distribution of flows is not highly skewed. Total withdrawals in the region amounted to 7.4 bgd (8.29 maf) in 1975 and are expected to decrease to 6.0 bgd (6.72 maf) by the year 2000. In contrast, total consumption is expected to increase to 1.1 bgd (1.23 maf) by the end of the century. Most of the increase will be for domestic and steam-electric uses with a decrease in the amount used for manufacturing.

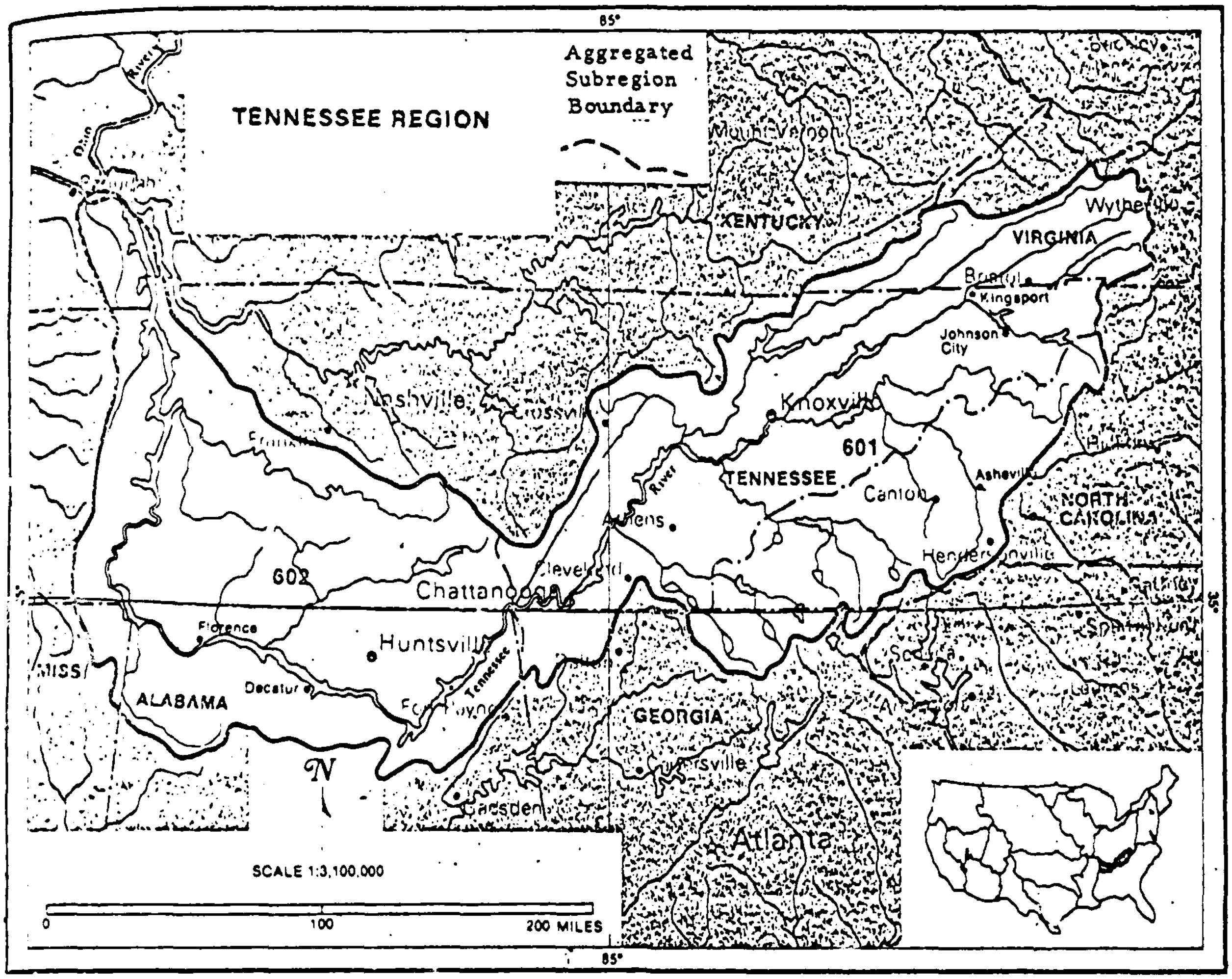


Figure 34. Location and drainage of the Tennessee Region

On a monthly basis, highest flows occur during December-March with February being the highest; flow variation is also large during these months. Monthly flows show little skewness with January and February being slightly skewed.

There is an apparent significant trend for increased annual flow (0.16 percent per year) from the eastern half but not in the western part of the region. Again, this trend may be related to differences in record length, 1938-1977 for the eastern and 1900-1977 for the western half. Both sections might show significant trends if analyzed for the same period, 1938-1977. Although this period coincides with the general cooling period (1940 to present), it could well result from land use practices such as increased urbanization.

Normal reservoir storage within the region is 3,600 bg (11.04 maf) and flood storage is 7,724 bg (23.7 maf). Flooding remains a problem in spite of the streamflow regulation imposed by TVA dams and reservoirs. Cities along the Tennessee River and its tributaries are frequently flooded during periods of excessive rainfall, although damage is not as great as in pre-TVA days. The average flood loss is $72 million dollars (1975) and damages are expected to reach $116 million by the year 2000 unless additional flood control measures are implemented.

Climatic records from Nashville, Tennessee and Asheville, North Carolina were used to develop possible changes in area runoff for the four climatic change scenarios. The $\overline{Q}$ scenario to $\overline{Q}$ present ratios for mean annual flows are shown in Table 8.

Scenario	Eastern	Western	Average
1 (warmer and drier)	.61	.65	.63
2 (cooler and wetter)	1.43	1.32	1.38
3 (warmer and wetter)	1.07	.06	1.07
4 (cooler and drier)	.86	.84	.85

Table 8. Estimated ratio of $\overline{Q}$ scenario to $\overline{Q}$ present for annual flows in the Tennessee Region.

Under scenario 1 (warmer and drier), a reduction of 63 percent of the present annual runoff is estimated for the region. Predicted annual runoff would be 25.9 bgd (29.0 maf) and is still well above the present 7.4 bgd (8.29 maf) withdrawal rate for 1975 and the projected value of 6.0 bgd (6.7 maf) for the year 2000. The amount is well below the 38.5 bgd (43.5 maf) suggested as necessary for optimal fish and wildlife habitats. Longer duration

base flows would result in poorer quality surface water. Local shortages could be eased by increased production of ground water from deep aquifers.

The mean annual runoff under scenario 2 (cooler and wetter) would be 1.38 times the present. This amounts to 56.72 bgd (63.53 maf) which is 15.61 bgd (17.5 maf) more than at present. The most obvious result of this increased runoff would be aggravated flooding along the mainstem of the Tennessee River as well as its tributaries. This would necessitate increased flood prevention.

The projected results from the two scenarios are detailed in Tables 11 and 12 in the Appendix.

REGION 07 - UPPER MISSISSIPPI RIVER

The Upper Mississippi River Region encompasses the drainage basin of the Mississippi River upstream from the mouth of the Ohio exclusive of the area drained by the Missouri River (Figure 35). The total drainage area is approximately 180,700 square miles and includes portions of Illinois, Indiana, Iowa, Michigan, Missouri, Minnesota, South Dakota, and Wisconsin.

The upper Mississippi is a key element in the nation's inland waterway system. Through channelization and use of locks and dams, the Mississippi has been developed for navigation from St. Louis to Minneapolis-St. Paul. Below St. Louis to the confluence with the Ohio at Cairo, Illinois, the Mississippi is an open river with dredging necessary to maintain adequate navigable depths. Other rivers within the region are also navigable but only for relatively short distances.

The average annual precipitation varies from 20 inches in the north to 48 inches in the south. In the southern part of the region, precipitation is about evenly distributed between winter and summer months. In the north, there is more precipitation during the growing season than in the winter.

Average annual temperature ranges from 39°F. in the northern portion to 59°F. in the southern part of the region. There is about a 3°F. change in annual temperature per 100 miles of latitude.

As of 1975, 47 percent of the region was being used for harvested croplands, 21 percent forest and woodland, 19 percent pasture and range, 8 percent in non-harvested croplands, 2 percent in urban and built up areas and 2 percent water surface area. The land use percentages are anticipated to remain roughly the same through the year 2000.

The forested areas are primarily located in the northwestern and southwestern parts of the region. Major forest types include aspen-birch and white-red-jack pine in the north and elm-ash-cottonwood, birch-maple, and oak-hickory in the south. Grasslands predominate in the eastern and western parts of the region and an intermingling of grasses and forest occurs in the central part. Major crops include corn, soybeans, oats, and hay.

Most of the region's topography is the result of glaciation which has produced a gently rolling terrain with progressively less well developed drainage as one moves northward. The distribution of ground water reflects this part of geology history.

Alluvium and outwash deposits constitute the most productive part of the ground water supply in this region. The alluvium of Holocene age consists of silt, sand and gravel and is present in the valley of the Mississippi River adjacent to many of the larger streams. These deposits are generally finer grained and less permeable than outwash deposits but can provide larger quantities of water locally. Outwash, which is composed predominantly of sand

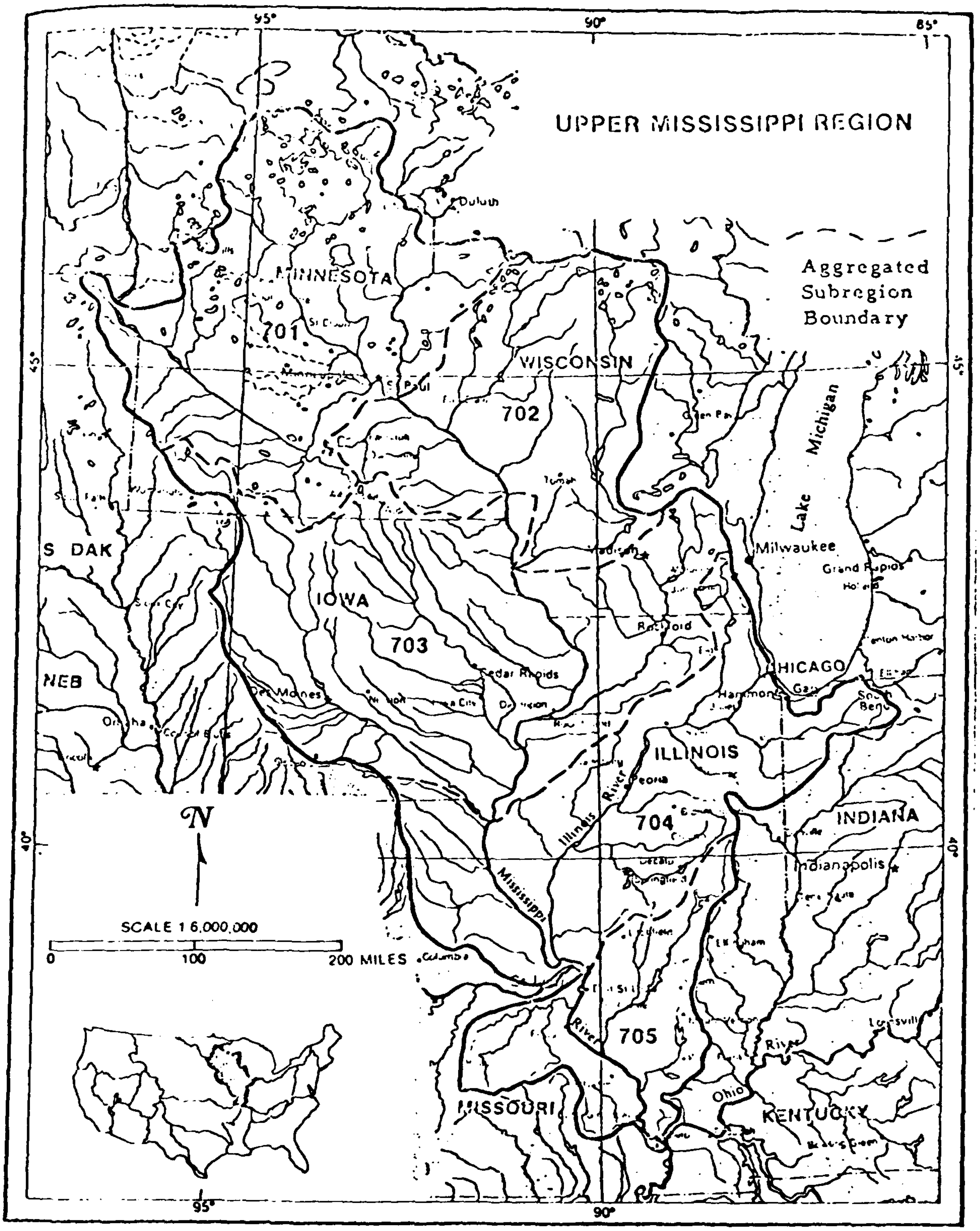


Figure 35. Location and drainage of the Upper Mississippi River Region

and gravel deposited by glacial melt-water streams is highly permeable and an excellent source of ground water. Outwash deposits are most prevalent in Minnesota and Wisconsin and usually undifferentiated from the alluvial deposits. In some places within the region, sand and gravel deposits occupy buried valley in the bedrock and are highly productive sources of ground water.

Till is the principal glacial deposit in the region and is generally low in transmissivity. It is a mixture of clay-silt-sand-gravel and is a poor source of ground water.

Ground water is a major source of water for municipal, industrial, agricultural, and other uses in the Upper Mississippi Region. In 1975, an estimated 2.37 bgd (2.65 maf) of water was withdrawn from ground water sources for all uses in the region. This total ground water use represents approximately 19 percent of total water withdrawals. Large quantities of ground water can be found in the unconsolidated glacial sediments of glacial drift located in the region. USGS estimates that approximately 43.0 bg (1.3 x 10^8 acre-feet) of potable water is in storage in the outwash and alluvial aquifers along. These unconsolidated sediments are especially excellent ground water sources along several of the region's major rivers where well yields are usually 40 to 500 gallons per minute (gpm) and, in many cases, more than 500 gpm. Bedrock aquifers are also major ground water resources in the region.

Three major bedrock aquifers are present in the region. They are the Mount Simon-Hinckley of Precambrian and Cambrian age, the Cambrian-Ovdovician, and the Silurian-Devonian aquifers. The Mount Simon-Hinckley aquifer is mostly sandstone and is present in southeastern Minnesota, western and southern Wisconsin, northern Illinois, and eastern Iowa. The Cambrian-Ovdovician aquifer system consists of several sandstone and dolomite formations and occurs in southeastern Minnesota, southern Wisconsin, northern Illinois, Iowa, northwestern Indiana, and eastern Missouri. The Silurian-Devonian aquifer consists of several limestone and dolomite formations and supplies water to wells in northeastern Iowa, northern Illinois, southeastern Wisconsin, and northwestern Indiana.

Ground water quality is generally good and suitable for most uses. The average annual regional recharge is about 23.0 bgd (25.76 maf).

Mean annual discharge from the region is 121.0 bgd (135.5 maf). Of this amount, 44.1 (49.4 maf) is inflow from the Missouri River system and 2.06 bgd (2.3 maf) is imported from Lake Michigan via the Illinois River. The remaining 76.0 bgd (85.1 maf) constitutes runoff generated within the region. Current consumption is estimated to be 1.14 bgd (1.28 maf) and is expected to increase to 2.69 bgd (3.01 maf) by the year 2000. Total water withdrawals in 1975 amounted to 12.4 bgd (13.9 maf) but this amount is expected to decrease to 7.9 bgd (8.85 maf) by the year 2000 due to decreases in manufacturing and steam-electric uses. An estimated 110.7 bgd (124.0 maf) streamflow is necessary for optimal fish and wildlife habitat conditions.

The mean annual flow from the region is equal to the median indicating the frequency distribution of the flows are nonskewed or Gaussian. The 5 percent exceedence flow is 189.0 bgd (211.7 maf) and the 95 percent exceedence is

65.3 bgd (73.1 maf); Q_{05}/Q_{95} is 2.9.

Monthly flow distribution is remarkably similar throughout the region. In the north and central portions of the region, high flows occur in April-July and low flows in August-February. The low flow months show relatively low variance as compared to the high flow months. The monthly distribution exhibits low to moderate skewness. In the southern part of the region the high and low flow months are the same as in the north and central portions but high flows have a greater tendency for persistence, probably representing higher base flow because of greater basin area. All records analyzed cover the period 1900-1976 and none show significant trends over that 77-year period.

Surface water storage capacity within the region is 4,230 bg (12.98 maf) for purposes other than flood control and 7,570 bg (23.22 maf) for flood control. The region is subject to frequent and often severe flooding primarily due to man's continual development and encroachment into flood plains. Sheet flow flooding also occurs causing excessive wetness of agricutural lands. Currently the region experiences an average annual flood loss of nearly \$235 million (1975). Without any future flood control development, damages are projected to reach \$380 million (1975) by the year 2000.

The effects of the climatic change scenarios have been appraised by computing the ratio of the estimated mean annual runoff under the assumed climatic change scenario to the estimated mean annual runoff at the present (Table 9). The precipitation-temperature stations used are St. Louis, Chicago and Minneapolis-St. Paul.

Scenario	South	Central	North	Average
1 (warmer and drier)	.63	.63	.60	.62
2 (cooler and wetter)	1.37	1.50	1.50	1.46
3 (warmer and wetter)	1.07	1.13	1.10	1.10
4 (cooler and drier)	.87	.88	.84	.86

Table 9. Estimated ratio of $\overline{Q}$ scenario/$\overline{Q}$ present for annual flows in the Upper Mississippi Region.

If scenario 1 (warmer and drier) is assumed, the present mean annual runoff from the region would be decreased to 62 percent of the present mean annual flow. Consequently, the 76.0 bgd (85.1 maf) mean annual runoff generated within the region would be reduced to 47.12 bgd (52.8 maf). If the inflow sources remain the same as present and if withdrawals plus consumption is estimated to be 15.0 bgd (16.8 maf) the remaining streamflow (<u>not</u> including

increased evapotranspiration) would be near 90 bgd (100.8 maf) somewhat less than the 110.75 bgd (124 maf) that is needed for optimal fish and wildlife habitat conditions. At present little irrigated agriculture occurs in the region but under this scenario, the amount of irrigation may have to be greatly expanded using both surface and ground water. However, it may not be economically feasible to convert to irrigated agriculture. Assuming the occurrence of scenario 2 (cooler and wetter), the mean annual runoff would increase 1.46 times above the present. The mean annual runoff generated within the region would be 111.0 bgd (124.3 maf). If inflow remained constant, and withdrawals plus consumption is 15.0 bgd (16.8 maf) the remaining streamflow (not countin reduced evapotranspiration) would be near 155 bgd (173.6 maf). The results of occurrence of scenarios 3 and 4 would probably be trivial. Tables 13 and 14 in the Appendix show the results expected to occur on different aspects of the hydrologic system.

REGION 08 - LOWER MISSISSIPPI REGION

The area and extent of the Lower Mississippi River Region is shown on Figure 36. It includes the drainage basin of the Mississippi River below its confluence with the Ohio River, except for parts of the Arkansas, Red and White Rivers above the backwater limits of the Mississippi. The region encompasses a drainage area of about 105,150 square miles and includes portions of Missouri, Tennessee, Kentucky, Arkansas, Mississippi and Louisiana. In general, water supplies are adequate and most water problems are related more to resource distribution than to availability. About 90 percent of the withdrawals are for steam-electric, manufacturing and irrigation, with amounts evenly divided between these three uses. Irrigation accounts for 76 percent of the water consumed within the region.

Average annual precipitation varies from 64 inches in the extreme southern part to 44 inches in the extreme northern end of the region. Average annual temperature is 70°F. in the south part and 60°F. in the north.

Present land use includes 51 percent in cropland, pasture and other agriculture; about 40 percent is forest, principally fast growing pines and high quality bottom-land hardwoods; about 3 percent is irrigated cropland; and 1.5 percent urban and built up areas. The amount of land used for urban purposes is expected to increase by about 70 percent, cropland by 10 percent, irrigated farmland by 30 percent and about 2.26 million acres drained and converted to cropland by the year 2000.

The lower Mississippi River and its alluvial valley became deeply incised in the coastal plains area during the last glacial advance of the Pleistocene, when sear level was several hundred feet lower than at present. The valley was gradually filled with alluvial deposits by the river forming a gently sloping, undulating lowland bordering the river in the region.

All the region, except for the Ouachita Mountains and Ozark Plateau is located in the Central Gulf Coastal Plains Province, an extensive lowland overlying unconsolidated sand, gravel, clay, silt, marl and limestone of Cretaceous to Tertiary age dipping generally southwestward into the Embayment area. The strata range in total thickness from zero in the extreme northeast to tens of thousands of feet in the south. They are mantled by terrace sand and gravel and loess and overlain by thick alluvium of Quaternary age. Almost all of the Coastal Plain formations include water-bearing beds, mostly sand and gravel, but also some limestone.

The region contains some of the most productive ground water areas in the United States, located mainly in the Yazoo Delta. Artesian sands of Tertiary age supply flowing wells through the delta. Even more productive, however are the Quaternary alluvium deposits with wells typically yielding 1,500 to 2,000 gpm in this aquifer. Many irrigation wells tap this source. Aquifers containing fresh ground water underlie the entire region except for part of the coastal area of Louisiana and a small area in the central part of that state. About 80 percent of these aquifers are capable of yielding large volumes of fresh

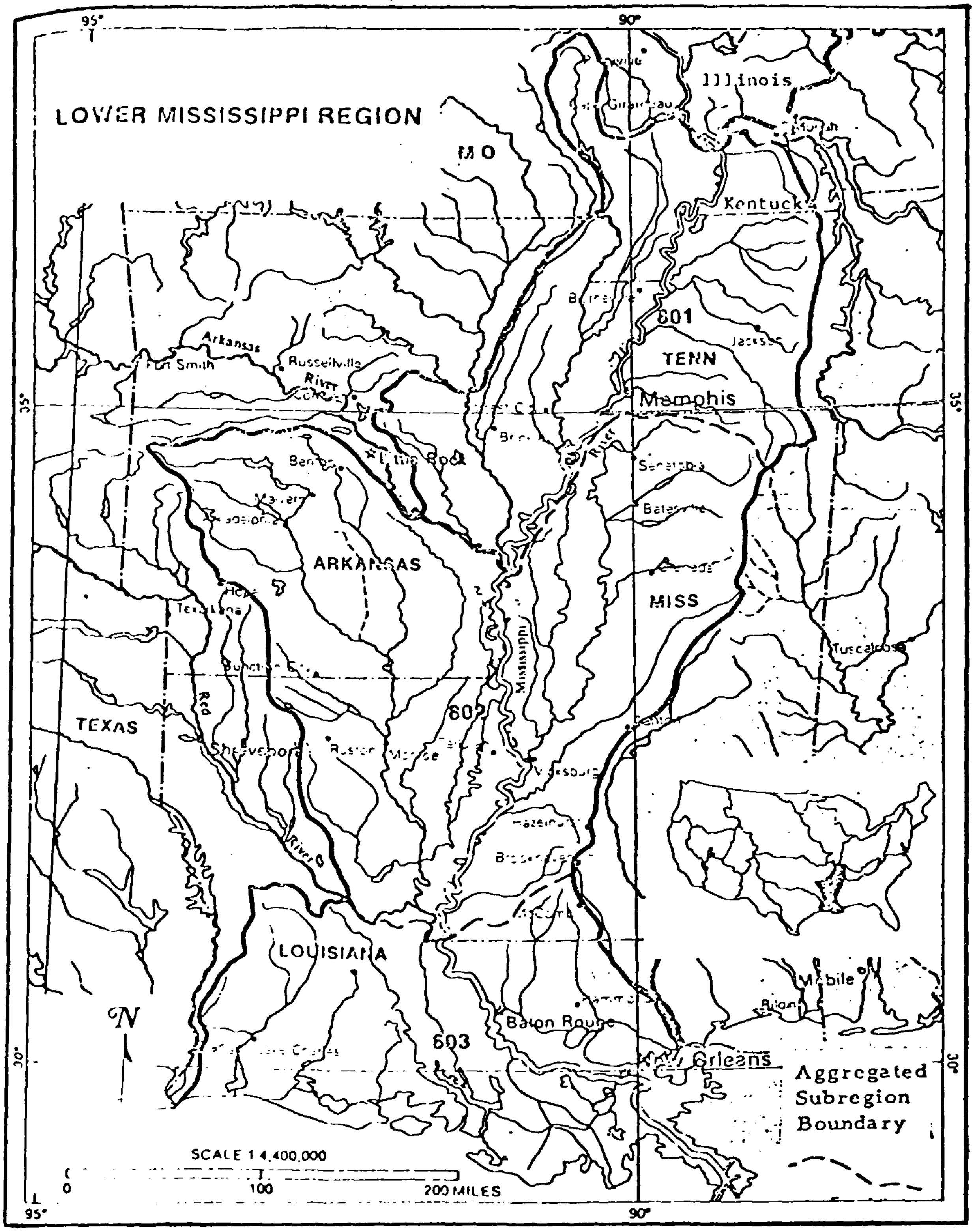


Figure 36. Location and drainage of the Lower Mississippi River Region

water. The highest yields can be obtained from sand and gravel alluvial and terrace deposits of Quaternary age. Yields of several thousand gpm are not uncommon. For the most part, the ground water supply potential is several times larger than present requirements. The region's average ground water supply is conservatively estimated at about 0.5 bgd (0.56 maf). This figure is based on economically and environmentally acceptable water-level declines.

Of the total annual streamflow from the region 433.0 bgd (485 maf), approximately 75.0 bgd (84 maf) represents runoff generated within the region, the remaining approximately 360.0 bgd (403 maf) is inflow from outside the region. The 5 percent exceedence flow is 757 bgd (848 maf) and the 95 percent exceedence flow is 202 bgd (226 maf). Q_{05}/Q_{95} is 3.75. Present 1975 consumption in the region is estimated to be 4.02 bgd (4.5 maf) of which 0.41 bgd (0.46 maf) is obtained by mining ground water. The amount consumed is expected to rise to 5.5 bgd (6.2 maf) by the year 2000 and the inflow is expected to decline by about 20.0 bgd (22.4 maf) to 341.8 bgd (382.8 maf) during the same period. Total annual withdrawals in the year 1975 amounted to 14.6 bgd (16.4 maf) and this amount is expected to rise to 24.8 bgd (27.8 maf) by the year 2000.

Low flows generally occur in August, September and October with high flows during March, April and May. The months with greatest variation in flow are December through July; the subset February-June, has the greatest probability of high flows. In general, the monthly flow distributions are highly skewed with the median being much less than the mean in almost all months. Obviously, there is a preponderence of low flow days in almost all months.

The period of record includes 1922-1977 and 1929-1977 and shows no significant trends in annual flows. Reservoir storage capacity in the region is not extensive. Normal storage is 2.034 bg (0.006 maf) and flood storage 6,398 bg (19.6 maf).

This region experiences some of the worst flooding within the United States. Average annual losses are estimated at $399 million, with $255 million to agricultural lands, $63 million to urban areas and $82 million in other damages. These high costs and frequent floods can be attributed to three main factors; 1) the region receives drainage from 41 percent of the conterminous United States, with intense activity often occurring during short periods; and 3) about one-half the land area of the region is subject to flooding from the river as well as tidal floods from hurricanes. Although flood damage control is highly sophisticated in the region, damages are projected to increase about 18 percent by the year 2000.

Structural improvements have been constructed throughout the region by joint efforts of federal, state, and local agencies. These include 3,800 miles of levees and flood walls, 11,555 miles of channel improvement, 42 pumping plants, numerous large and small reservoirs with a combined flood storage capacity of more than 6 million acre-feet.

The precipitation and temperature records for New Orleans and Memphis were used to assess the postulated changes in area annual runoff for the

region. The ratio $\overline{Q}$ scenario to $\overline{Q}$ present for the 4 climatic change scenarios is shown in Table 10.

Scenario	North	South	Average
1 (warmer and drier)	.72	.68	.70
2 (cooler and wetter)	1.36	1.37	1.37
3 (warmer and wetter)	1.08	1.17	1.13
4 (cooler and drier)	.89	1.00	.95

Table 10. Estimated ratio of $\overline{Q}$ scenario/$\overline{Q}$ present for annual flows in the Lower Mississippi Region.

A scenario 1 (warmer and drier) climatic change as envisioned would reduce mean annual runoff to about 70 percent of the present. Since the majority of the streamflow in the region (362 bgd, 405 maf) comes as inflow from outside, the total availability would depend on that source. However, if only the runoff generated in this region is considered, the estimated 75 bgd (85 maf) of the present would be reduced to 52.5 bgd (58.8 maf). This amount is still well above the projected total withdrawal of 24.8 bgd (27.8 maf) for the year 2000. The total effect would depend on the climate in the adjoining region from which the inflow comes. But assuming an across the board reduction in the streamflow by 30 percent, the 433.0 bgd (485.0 maf) would be reduced to 303.0 bgd (339.4 maf), well above the 80 percent exceedence flow of 282.0 bgd (315.8 maf). Low flows would become more predominant. Increased channelization would be necessary on the Mississippi River. Agricultural water shortages could be alleviated by increased usage of groundwater. Pollution would likely increase with low flows and salt water encroachment would probably occur. Scenario 2 (cooler and wetter) is postulated to increase the present mean annual flow by 1.37 times. This would mean an average annual streamflow of 593.2 bgd (664.4 maf) somewhat less than the present 5 percent exceedence flow of 757.0 bgd (847.8 maf). Flooding would become a problem with increased reservoir capacity necessary to store flood waters. Lowlands would be inundated and would have to be protected by levees or drained.

It is postulated that scenario 3 and 4 changes would have only trivial effects (Table 10). Details of the speculated impacts such climatic changes would ahve on the water resources system are shown in Tables 15 and 16 in the Appendix.

REGION 09 - SOURIS-RED-RAINY REGION

The Souris-Red-Rainy Region is shown on Figure 37 and encompasses about 54,750 square miles in the drainages of the Souris, Red and Rainy Rivers. The three rivers are international, either forming the border between the United States and Canada or flowing from one country to the other. Flow is generally northward to Hudson Bay. In the United States, the region is almost equally divided between the states of North Dakota (56 percent) and Minnesota (44 percent).

The region has a continental climate, characterized by extreme temperatures which have been known to vary from -54°F. to 118°F. Mean annual temperature is 40°F. Normal precipitation ranges from about 14 inches in the west to 28 inches in the east. While the amount is adequate for crop production in normal years, periods of drought are frequent, especially in the western part of the region.

Agriculture dominates the land use, with 39 percent of the land in harvested crops, 20 percent in non-harvested cropland, and 12 percent in pasture, range, etc. Primary crops include wheat, barley, oats, flax, corn, potatoes, soybeans, sunflower and sugar beets. Forests cover 14 percent of the area. These are largely of spruce and fir located in Minnesota and along the Canadian border.

Land use changes expected by the year 2000 include an increase in irrigated farmland from the present 36,000 to 311,000 acres (a particular development for 1,550,000 acres of irrigated farmland is reported in USGS Professional Paper 813-K). About 460,000 acres are expected to be converted to cropland either by clearing forests or draining wetlands.

In relatively recent geologic time, the region was covered by a continental glacier and as a result the land surface has broad divides and many potholes, sloughs and lakes. Most of the region is covered with glacial deposits ranging in thickness from less than a foot to several hundred feet. Sand and gravel deposits in the glacial drift form the most important aquifers. The region is underlain by a series of bedrock units that differ greatly in thickness and hydraulic character. They range in age from Precambrian to Quaternary. Precambrian, Paleozoic, Cretaceous and Tertiary rocks all serve as aquifers in the region but generally yield less than 100 gpm to wells. The drift aquifers yield less than 100 gpm but range from 5 to 1,000 gpm to wells. In many places the ground water is poor in quality with high amounts of dissolved solids.

The total average annual streamflow from the region amounts to 6.0 bgd (6.7 maf). The median is 5.6 bgd (6.3 maf) indicating skewness toward the lower flows. The 95 percent exceedence level is 8.1 bgd (9.1 maf) and the 5 percent exceedence level is 11.4 bgd (12.8 maf); Q_{05}/Q_{95} is 1.4. Total mean annual runoff from the region is estimated to be 6.1 bgd (6.8 maf). Presently (1975) 0.11 bgd (0.12 maf) are consumed in the region but this is expected to rise to 0.45 bgd (0.50 maf) by the year 2000 due largely to increases in

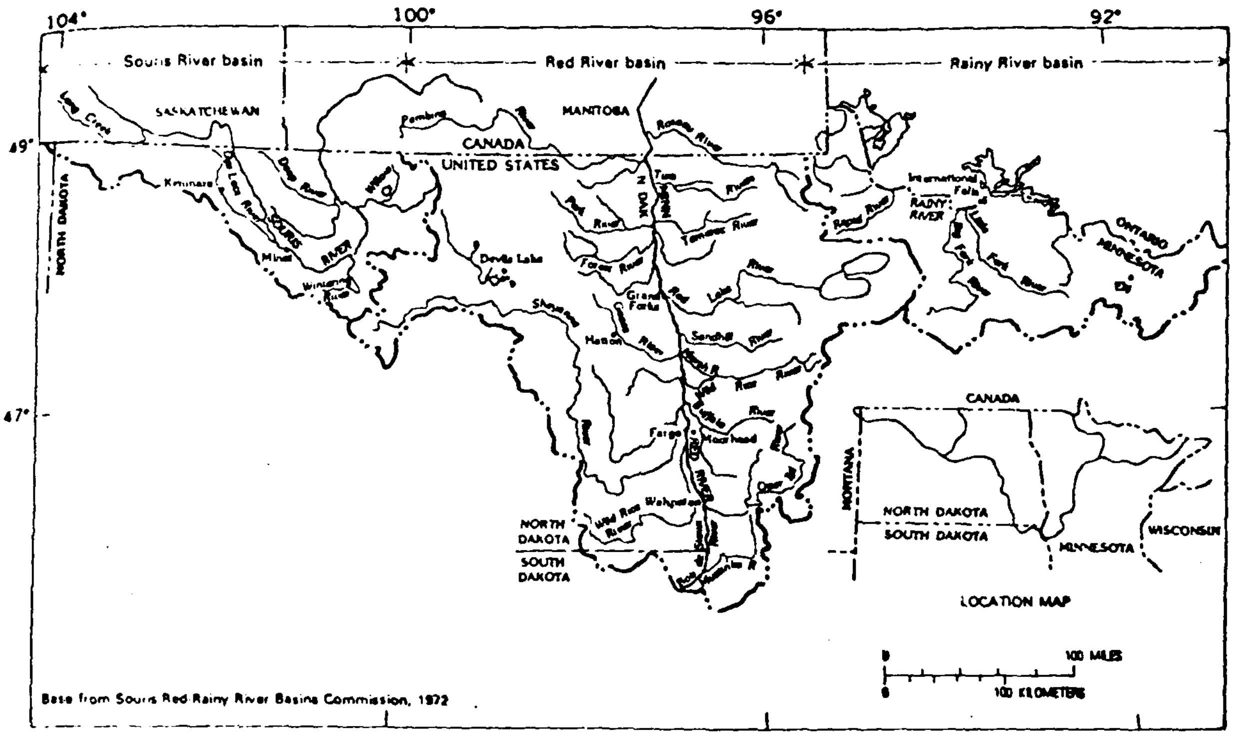


Figure 37. Location and drainage of the Souris-Red-Rainy Region

irrigated agriculture. The 1975 withdrawals amounted to 0.34 bgd (0.38 maf) and this is expected to increase to 0.60 bfd (0.67 maf) by the year 2000. Irrigation uses are expected to increase from the present 14 percent to 74 percent by then. Decreases are expected in steam-electric and manufacturing uses.

The monthly distribution of streamflow is highly variable and skewed. Low flow months are August-May when little or no flow may occur. Maximum runoff generally occurs in April and May (from snow melt) but the baseflow continues relatively high through June and July. Greatest variability in flows is in April and May with June and July somewhat less. The low flow months show very little variation.

A significant trend of 0.807 percent increase per year exists for streamflow during the period of record, 1909-1977. This trend is most likely related to shifts in land use rather than climate change.

Water storage facilities are inadequate in the region. Normal storage is 1,430 bg (4.4 maf) and flood storage is 2,430 bg (7.5 maf). Flooding is an extreme problem in the area especially along the Souris and Red Rivers. Both urban and rural areas, including large tracts of productive agricultural lands are subject to annual flooding. The damages totaled $39 million in 1975 and is expected to rise to $47 million (1975) by the year 2000.

For analysis of the postulated climatic change scenarios, precipitation and temperature records from International Falls, Minnesota, and Fargo, North Dakota have been used. The estimated ratios of mean annual runoff for the climatic change scenarios and the present annual flow are shown in Table 11.

Scenario	Central	East	Average
1 (warmer and drier)	.50	.60	.55
2 (cooler and wetter)	1.75	1.60	1.68
3 (warmer and wetter)	1.00	1.10	1.05
4 (cooler and drier)	1.00	.90	.95

Table 11. Estimated ratio of $\overline{Q}$ scenario/$\overline{Q}$ present annual flows in the Souris-Red-Rainy Region.

The postulated effect of a climatic change as described by scenario 1 (warmer and drier) would be a reduction of 45 percent in the present mean annual flow. The mean annual runoff from the region would be reduced to

3.4 bgd (3.8 maf) equal to present 80 percent exceedence level, but well above the 0.6 bgd (0.67 maf) projected withdrawal level of 2000.

Climatic change scenario 2 (cooler and wetter) would result in an increase in the mean annual flow to 1.68 times greater than the present. The total mean annual runoff would be increased to 10.25 bgd (11.5 maf). Obviously, the flooding problems of the present would be increased but presumably this could be helped by construction of storage reservoirs. The increased supply is considered to be a positive effect for agricultural reasons.

A more complete analysis of the speculated impact of these two climatic change scenarios on the water resources of the region are shown in Tables 17 and 18 in the Appendix.

REGION 10 - MISSOURI REGION

The location and extent of the Missouri Region is shown on Figure 38. It encompasses one-sixth of the conterminous United States and drains 511,000 square miles in the USA and 700 square miles in Canada. The region includes all of Nebraska and parts of Montana, Wyoming, North Dakota, South Dakota, Colorado, Iowa, Minnesots, Kansas and Missouri. The Missouri River is formed by the junction of the Jefferson, Gallatin and Madison Rivers in Montana and flows southeasterly 2,315 miles to its junction with the Mississippi near St. Louis.

Climate of the region is characterized by extremes in temperature, precipitation and wind movement. Precipitation varies from 40 inches in some parts of the Rocky Mountains and the extreme southeast, to as low as 6 inches in the rain shadow of the Rockies. Droughts are common and may be prolonged and severe. These may be interspersed with abundant rainfall accompanied by flooding. Average annual temperatures range from 40°F. in the northwest to 55°F. in the southeast. Extremes have ranged from -60°F. in Montana to summer highs of 120°F. in much of the plains region. High winds are common, especially in the plains area. These cause blowing dust during dry summers and blizzard conditions during the winter. High winds during periods of high temperature and deficient moisture can dessicate range and cultivated crops in a few days.

Land use is dominated by agriculture; 80 percent of the land area is in cropland, range, pasture, etc. Cultivated lands occur where rainfall is adequate or where irrigation water is available. Currently about 9½ million acres are irrigated; total cropland is about 106 million acres. Forest occur mainly in the Rocky Mountains, the Black Hills and the Ozarks. Woodlands are generally restricted to streambanks throughout the plains. Less than one percent of the land is urban; major centers include Kansas City, Denver, Omaha and Lincoln.

The rugged Rocky Mountain system forms the western boundary of the region and is the primary source of water in the region. The Great Plains extend eastward from the Rockies and constitute the major portion of the region. The Ozark Plateau province occupies the southeastern part of the Region.

The Rockies are primarily Precambrian igneous and metamorphic rocks. Along the eastern flank, Palezoic and Mesozoic rocks are exposed and dip eastward into the Great Plains. These rocks consist of limestones, sandstones and thick sequences of shale. In many places they are overlain by Tertiary sandstones, above which occur Pleistocene and Recent sands and gravels. Many of the sands and gravels occur only along the larger stream channels.

The Ogallala Formation of Pliocene age is the primary aquifer in the region. Irrigation wells in eastern Colorado, western and central Nebraska, eastern Wyoming and northwestern Kansas produce large quantities of water from this sources. The Pleistocene and Recent sands and gravels also produce large quantities of water along major stream channels. In most of the region,

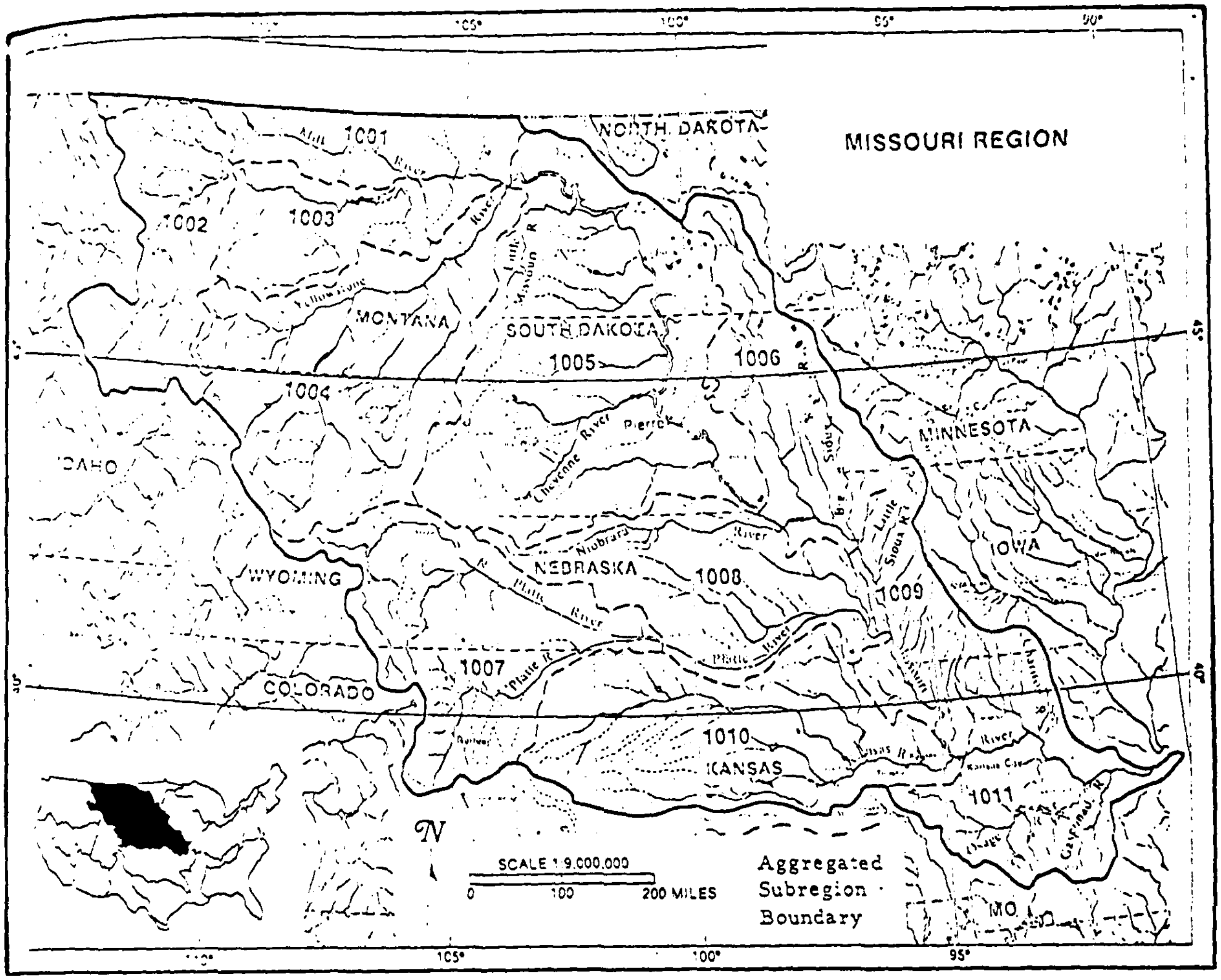


Figure 38. Location and drainage of the Missouri Region

ground water withdrawals are far in excess of recharge to these major aquifers. Glacial outwash serves as an important aquifer in a rather limited area north and east of the Missouri River in Montana and North Dakota. Bedrock aquifers (underlying the Tertiary beds) provide small to medium amounts of water to wells. The upper Cretaceous Laramie Formation and Fox Hills Sandstone include thin water bearing sandstone units. In many areas, these aquifers are underlain by the thick, nonwaterbearing Pierre Shale making deeper production unprofitable. In other areas, because of structure or thinning of the Pierre, the underlying Dakota Sandstone is either exposed or near the surface and serves as a highly productive aquifer. However, in some areas of Kansas, salt water occurs in the Dakota.

As mentioned above, present consumption of fresh water in this region averages 15.5 bgd (17.4 maf) per year. Of this amount, 92 percent is used for

agriculture. This amount is expected to rise to 19.9 bgd (22.3 maf) of which 83 percent will be for irrigation by the year 2000. Much of this will come from ground water sources.

Total 1975 average ground water withdrawals in the region amounted to 10.4 bgd (11.65 maf) second largest of all regions. An estimated 2.5 bgd (2.8 maf) is in excess of recharge. It is estimated that at the current rate of depletion one-half of the total available ground water stored in the region will be depleted in a little over 200 years. However the life of heavily used aquifers, such as the Ogallala, which receives very little recharge may be much shorter.

Mean annual surface water flow from the region is estimated to be 44.1 bgd (49.4 maf). The median flow is 43.2 bgd (48.4 maf) indicating very little skewness; the 5 percent exceedence flow is 74.3 bgd (83.2 maf) and the 95 percent exceedence level is 17.6 bgd (19.7 maf); Q_{05}/Q_{95} is 4.2. Total annual runoff is estimated to be 61.52 bgd (68.9 maf). About 0.41 bgd (0.46 maf) are imported into the basin each year from the Upper Colorado River basin. It is estimated that 2.56 bgd (2.87 maf) is mined from the ground water reservoirs. Within region consumption is estimated to be 15.46 bgd (17.3 maf) and evapotranspiration losses are 4.9 bgd (5.5 maf) per year.

By the year 2000, annual imports are expected to increase slightly, to 0.50 bgd (0.56 maf), but consumption is expected to rise to 19.9 bgd (22.3 maf) and evaporation will increase to near 6.0 bgd (6.7 maf). Exports from the basin will be 0.64 bfd (0.72 maf) leaving a remaining stream outflow of 35.84 bgd (40.14 maf). The amount of streamflow necessary for optimal fish and wildlife habitat conditions is 33.96 bgd (38.04 maf).

Monthly distribution of streamflow is highly variable in time and space. Mountain snowmelt in late spring (May) and early summer (June) provides much of the streamflow in the western and northern parts of the region. This serves as most of the reservoir inflow farther downstream. In the northern part of the area drained by the Milk River the streamflow mean and variance is remarkably uniform throughout the year, although a slight maximum occurs in February, March and April. The area south of the Milk has a similar distribution. In the western mountainous area, maximum runoff from snowmelt occurs in May, June and July. The remaining months have little to no flow. In the east, central, and southern parts, maximum runoff occurs during the months of July-September as result of summer and early fall precipitations. Analysis of the annual flow series for the period 1924-1976 and for 1903-1976 indicated there are no significant trends in the annual runoff series.

Runoff varies considerably over the whole region ranging from as much as 20 inches in the higher western mountains to less than 0.25 inches in the central parts of North and South Dakota and to near 15 inches near the mouth of the Missouri River.

Reservoir capacity is greater than that for any other region. Normal storage capacity is 27,161 bg (83.3 maf) and the amount allocated to flood control is 38,488 bg (118.06 maf). The system includes 6 large mainstem and numerous tributary reservoirs. The mainstem reservoirs control streamflow

for a number of purposes including a 9-foot navigation channel for the 732-mile reach of the river from St. Louis to Sioux City, Iowa.

Flooding remains a problem in many areas during periods of excessive rainfall. This in spite of the large amount of reservoir capacity dedicated to flood control. The fact that many cities and towns were historically located along rivers, which were a major avenue for commerce, aggravates the control problem.

Numerous discussions have been held concerning proposed interbasin transfers but only a few have been implemented. Currently, water is diverted from the Missouri basin into the Souris-Red-Rainy Region for use in North and South Dakota. Water is imported into the region from the Colorado River Basin for use in Colorado and Wyoming.

Competition for water is strong within the region, as is the case in most areas where demand exceeds supply. There are many claims for water that have not be quantified, including those of Indian tribes and the Federal Government. Thus, the total amount of water needed in the region by the year 2000 is highly uncertain.

Temperature and precipitation data from Lincoln, Nebraska, Fargo, North Dakota, and Yellowstone, Wyoming were used to construct the various climatic change scenarios. The estimated changes are expressed by the ratios of $\bar{Q}$ scenario to $\bar{Q}$ present shown in Table 12 for each of the four scenarios.

Scenario	East	Central	West	Average
1 (warmer and drier)	.40	.25	.43	.36
2 (cooler and wetter)	2.00	1.75	1.17	1.64
3 (warmer and wetter)	1.00	1.25	1.00	1.08
4 (cooler and drier)	1.00	1.00	1.00	1.00

Table 12. Estimated ratios of $\bar{Q}$ scenario/$\bar{Q}$ present for annual flow in the Missouri River.

In a region of limited rainfall and increasing demand, such as this area, a slight rise in temperature associated with a decline in precipitation could have a tremendous local effect on water availability. For climatic change scenario 1 (warmer and drier), it is estimated that such a change could result in as much as a 65 percent reduction in the present mean annual runoff. For example, total average basin wide runoff would be reduced from an estimated 1.5 inches to about 0.5 inches per year. In addition, the annual flows would

likely become more variable, more skewed (toward low flows) and less persistent. On possible result would be large decreases in surface reservoir yield. Because of decreasing surface water supplies, it would be anticipated that increased production from ground water sources would be necessary for agricultural purposes. This would place additional stress on aquifers that are already being mined under present conditions and greatly decreasing the expected life of the principal ground water sources. Except for the Pacific Northwest Region, adjoining regions would probably experience similar shortages making intraregional diversions of questionable value.

A scenario 2 type change (cooler and wetter) could, in contrast, result in 1.65 times as much annual runoff as presently. This would mean a total of near 2.50 inches of runoff per year which would provide much needed water for the region. The results would be greater surface reservoir yield and improved recharge to presently heavily mined aquifers. Additional available surface water may result in a decline in ground water use for agriculture. The overall water system response would be good with the present large surface water storage being very beneficial.

Estimates of climatic change impacts on the water resources system of the region are shown in Tables 19 and 20 in the Appendix.

REGION 11 - ARKANSAS-WHITE-RED REGION

The Arkansas-White-Red River Region, shown on Figure 39, encompasses an area of nearly 244,000 square miles. Three major rivers, the Arkansas, White and Red drain the region which includes all of Oklahoma, and parts of Arkansas, Texas, Louisiana, Colorado, New Mexico, Kansas and Missouri.

Climate of the region varies from semi-arid in the west to humid in the east. The western half experiences temperature extremes and moisture deficits associated with the intrusion of arctic air in the winter and hot, dry winds from the interior of Mexico during the summer. Warm, moist air from the Gulf of Mexico has a major influence on weather conditions in the eastern section. Average annual precipitation ranges from 20 inches in the far west of the region to 55 inches in the eastern most part. Mean annual temperature ranges from 40°F. in the western most part to 65°F. in the eastern portion.

Natural vegetation is highly variable with the region ranging from the alpine zone in the high Rockies through short grass on the plains, and upland hardwoods in Arkansas to bottom-land hardwoods in the Mississippi Delta area.

Agriculture is the dominant land use with croplands and pasture, including irrigation, accounting for about 76 percent of the area. Forests occur on 21.5 percent of the land and urban developments on about 1 percent. Future estimates call for the elimination of 191 thousand acres of forest and 787 thousand acres of pasture lands to be converted to cropland by drainage between 1975 and 2000. Irrigated land is expected to increase from 4.8 million to 5.5 million acres.

The region is characterized by a diverse physiography and geology and in turn by diversity in water resources and related problems. The principal physiographic features of the region are the high southern Rocky Mountains in the west, the low mountains of the Ozark Plateau and the Ouachita provinces in the east and the intervening broad expanse of the Great Plains and Central Lowlands sloping from west to east. A small part of the Gulf Coastal Plain is present in the extreme southeastern corner of the region.

Surface and subsurface geologic conditions vary tremendously as to rock type and expanse over the region. Precambrian igneous and metamorphic rocks outcrop in the Rocky Mountains of Colorado and New Mexico and in the mountains of Missouri, Arkanasas, Oklahoma, and Texas. Paleozoic rocks consisting of well indurated sandstones and limestones outcrop extensively in Colorado, New Mexico, Missouri, Arkansas, Oklahoma and Texas. Some yield small amounts of water to wells.

Mesozoic rocks of sandstones and shales outcrop in all of the region except Louisiana. These rock units, primarily from the Cretaceous period produce moderate amounts of water in the region.

Rocks of Ceneozoic age blanket large portions of the region. Rock types include siltstone, shale, sandstone and unconsolidated silt, sand and gravel.

Most significant ground water production is from these rocks of youngest geologic age.

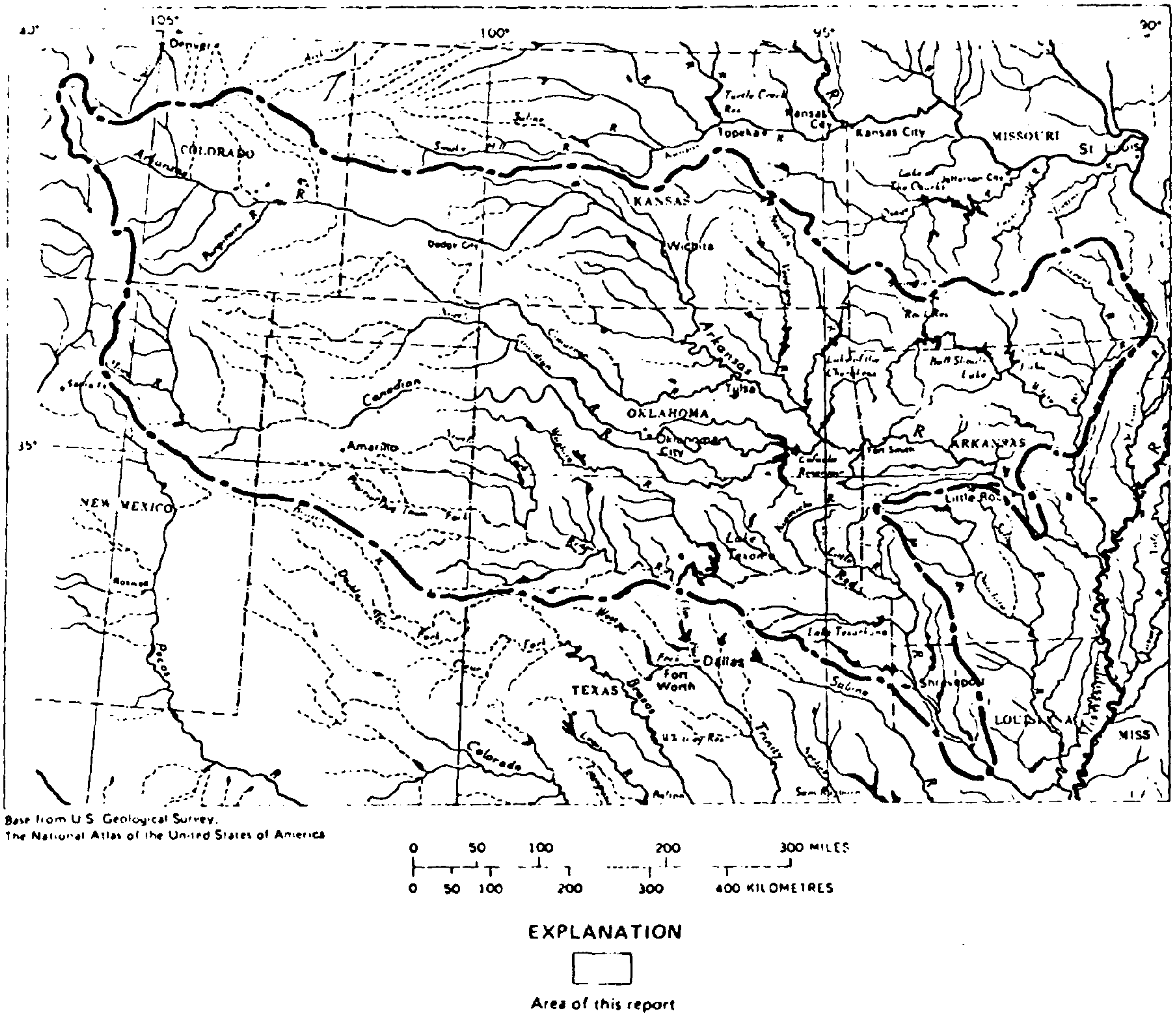


Figure 39. Location and drainage of the Arkansas-White-Red River Region

Total ground water produced in the region in 1975 is estimated to be 8.8 bgd (9.9 maf) of which 5.5 bgd (6.2 maf) is in excess of recharge. Much of this production is from stream valley alluvial aquifers that are in direct hydraulic connection with the surface water. The Ogallala Formation also produces large amounts of ground water primarily for irrigation. However, this aquifer receives little recharge from surface water and is currently being heavily mined. In fact it is estimated that one-half of the total present

water in storage for the region will be depleted in the next 125 years. The portion of the region where the Ogallala serves as a major water source is shown in Figure 40 and as is apparent from comparison with Figure 41, this is the area of natural water deficiency in the region. The life of the Ogallala will likely be much shorter than the 125 years mentioned above. A summary of the characteristics of the principal aquifers in the region is shown in Table 13.

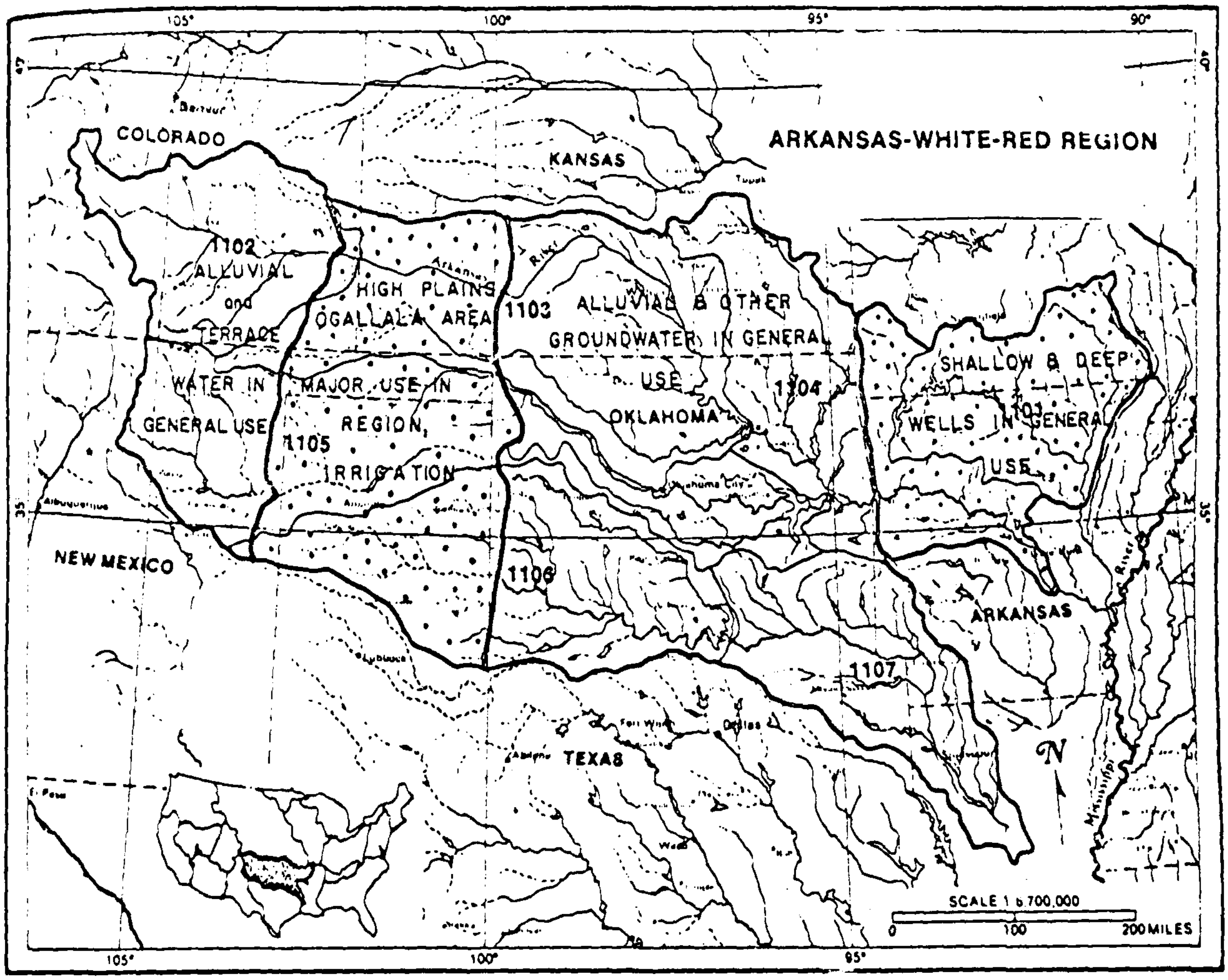


Figure 40. Distribution of major aquifers in the Arkansas-White-Red Region.

Regionally, the water resource consists of an average annual runoff of about 6 inches from 265,000 square miles. Ground water storage is estimated to be 6.5 x 10^5 bg (2,000 maf). As shown in Figure 41, the majority of the

Region

gion is water deficient so the 6 inches of annual runoff is misleading as to general supply.

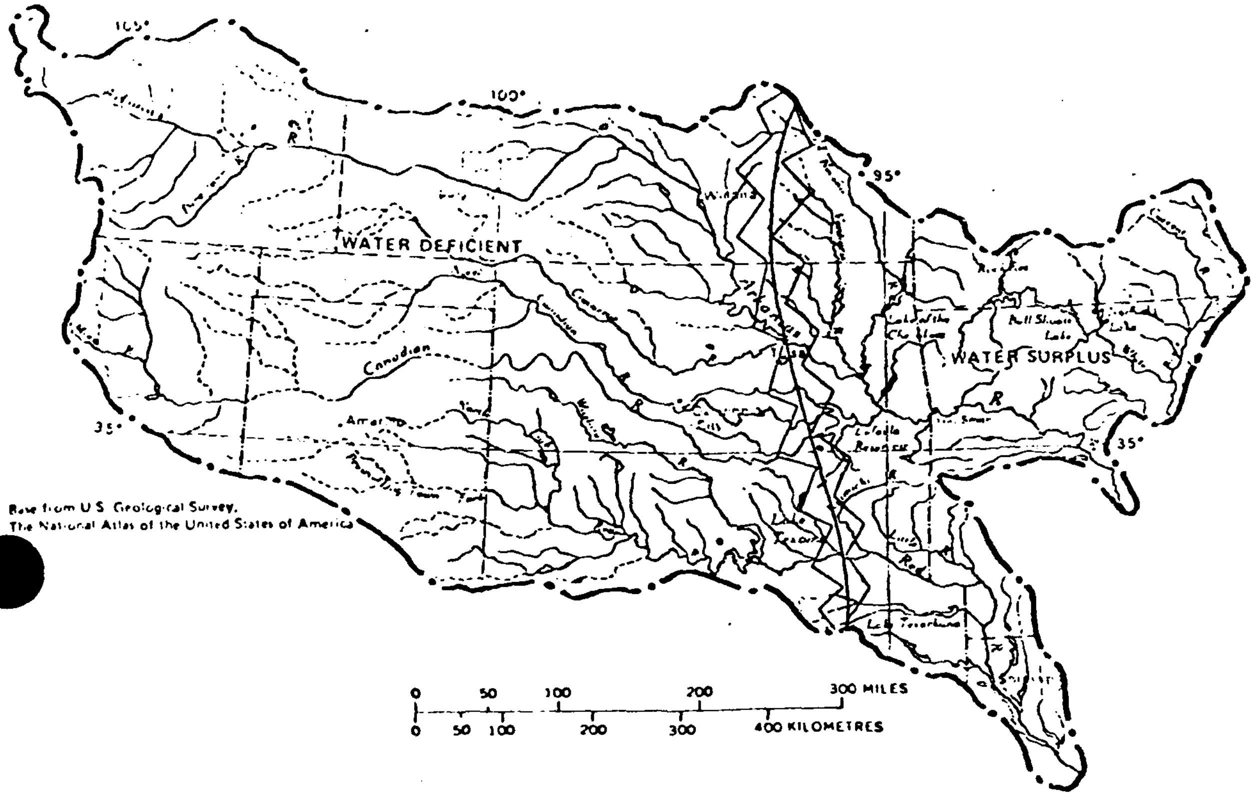


Figure 41. Division of the Arkansas-White-Red Region according to water availability.

The mean streamflow from the region is 62.6 bgd (70.1 maf) and the median is 59.1 bgd (66.2 maf). 5 percent of the time, the flow exceeds 120.7 bgd (135.2 maf) per year and 95 percent of the time it exceeds 21.6 bgd (24.2 maf); Q_{05}/Q_{95} is 5.6. The total annual runoff from the region is 67.7 bgd (75.8 maf). A small amount of water is imported (mostly from the Colorado River Basin) each year, about 0.16 bgd (0.18 maf); this is expected to increase to 0.23 bfd (0.26 maf) by the year 2000. Mining of ground water is excessive, about 5.46 bgd (6.12 maf). Consumption is 8.01 bgd (8.97 maf) and evaporation losses are 2.61 bgd (2.92 maf). These two requirements combined are expected to rise about 12 percent from 10.7 bgd (12.0 maf) to 12.1 bgd (13.6 maf) by the year 2000. Of the remaining streamflow, 62.6 bgd (70.1 maf), it is estimated that 46.1 bgd (51.6 maf) are necessary for optimal fish and wildlife habitat conditions.

Aquifer type	Nature of rock	Thickness (ft)	Areal extent	Depth to water (ft)	Hydraulic conductivity (ft/d)	Well yields (gal/min)	Development and use	Ground water in storage (acre-ft x 10^6)
Stream valley alluvium	Sand and gravel	50-200	Along large streams in flood plains. Extensive in Coastal Plain of Arkansas and Louisiana.	0-30	100-1,500	300-5,000	Extensive, principal source of ground water; frequently overdeveloped. Not used in some areas.	2.8
Terrace alluvium		50-600	Plains of Texas, New Mexico, Colorado, Kansas, and Oklahoma.	50-300	10-700	50-1,000	Extensive, subject to overdevelopment and water mining, particularly in High Plains of Texas.	4.1
Alluvium of intermontane valleys and buried alluvial valleys		100-5,000	Arkansas River basin in Colorado.	0-50				8.2
Carbonate and gypsum	Limestone and dolomite, and gypsum beds. Generally a dense rock, but subject to solution along fracture and bedding planes.	50-1,500	Limestone and dolomite in southern Missouri, northern Arkansas, southeastern Kansas, and Oklahoma. Gypsum in Oklahoma and Texas.	30-450	50-1,500	50-1,000	Moderately to heavily developed, overlooked as a source of water in some areas. More subject to pollution than other aquifers because of cavernous nature.	3.2
Sand and sandstone	Sand grains ranging from very fine to coarse. Generally cemented with siliceous material or carbonate. Unconsolidated in the Coastal Plain.	100-500	Sandstone principally in Kansas, New Mexico, and Oklahoma. Sand in Coastal Plain of Arkansas, Texas, and Louisiana.	20-300	([1])	10-1,000	Extensive, subject to overdevelopment and water mining. Loss of artesian head in many areas ranging from 2 to 300 feet.	7.9
Undifferentiated sandstone, carbonate, shale, or basalt	Consolidated rocks, including sandstone, interbedded shale, carbonate, and crystalline igneous rocks.	100-5,000	Sandstone, carbonate, and shale locally throughout region; basalt in parts of New Mexico, Colorado, and northwestern Oklahoma.	1,200	([2])	5-50	Mainly domestic use, not heavy, concentrated use, because of low permeability and low well yields. Difficult to predict well yields.	2.2

[1] Generally less than 100 ft/d
[2] Generally less than 10 ft/d

Table 13. Aquifer types and hydrologic characteristics for ground water sources in the Arkansas-White-Red Region

Total annual fresh water withdrawals in the region in 1975 amounted to 12.87 bgd (14.4 maf). This is expected to rise by 3 percent to 13.33 bgd (14.9 maf) by the year 2000. Presently, irrigation is the big user, 78 percent, and a slight decrease to 73 percent is expected by the year 2000.

Monthly distribution of streamflow varies greatly over the region. In the Ozark Plateau region, maximum runoff occurs during April and May. However, it is also fairly high in December, January, February and March. Low flow months are July, August, September, October and November. In the western part of the region, the runoff is from snowmelt in the Rocky Mountains. The high flow month is June with a second peak in August. All months are highly skewed toward the right. There is generally little flow during the period October-April. Toward the central part of the region, the high flow months are April, May and June but all months show considerably more variance than for the western most segment. Along the lower reach of the Red River, high flow occurs in May and June but also in October. There appear to be little if any significant trends in the runoff series.

Reservoir storage capacity is relatively high. Normal storage is 9.853 bg (30.2 maf) and flood storage is 22,761 bg (69.8 maf).

Surface water quality of the mainstream flows of the Arkansas and Red Rivers remain generally unsuitable for domestic use throughout their lengths. However, a number of tributary streams with good quality water are encountered in the eastern part of their watersheds. Several of the states and municipalities have developed or proposed development of those streams as water sources to supply the eastern and central portions of the region.

The stations used to analyze the climatic change scenario include Little Rock, Arkansas, Wichita, Kansas, and Colorado Springs, Colorado. The relationship of $\overline{Q}$ scenario to $\overline{Q}$ present annual runoff with respect to the four climatic change scearios is shown in Table 14.

Scenario	East	Central	West	Average
1 (warmer and drier)	.74	.25	.40	.46
2 (cooler and wetter)	1.39	1.75	3.00	2.05
3 (warmer and wetter)	1.16	1.00	1.00	1.05
4 (cooler and drier)	.87	.75	1.00	.87

Table 14. Estimated ratios of $\overline{Q}$ scenario/$\overline{Q}$ present for annual flows in the Arkansas-White-Red Region.

The results of the same type of relationship except based on average temperature and precipitation for the entire region is shown in Table 15.

Scenario	Ratio of $\bar{Q}$ scenario/$\bar{Q}$ present
1 (warmer and drier)	.40
2 (cooler and wetter)	1.80
3 (warmer and wetter)	1.10
4 (cooler and drier)	1.00

Table 15. Ratio of mean annual runoff for climatic scenarios to that for the present, but based on regional averages of temperature and precipitation.

The results obtained by the two approaches are quite similar except the results shown in Table 14 show the tremendous within region variation in climate.

Scenarios 1 and 2 remain to be the only two scenarios that appear to be important. It is estimated that a climatic change as outlined by scenario 1 (warmer and drier) would result in an average reduction in regional runoff of from 50 to 60 percent. Obviously such a reduction would have profound effects on the economy of the region. The total annual runoff would be reduced to 34.0 - 40.0 bgd (38.1 - 44.8 maf). This would create severe water shortages, deterioration of water quality for the remaining flow and a tremendous increase in ground water production from the already heavily mined major aquifers. This decline in available water associated with increasing demand as water rights as disputes are settled, would place the present water supply system under tremendous stress.

A scenario 2 (cooler and wetter) occurrence would result in an estimated increase in mean annual flow equivalent to about 2.0 times the present. This would increase the average total annual runoff to about 135.0 bgd (151.2 maf). Obviously increased flooding would be a major problem but a lot of water shortage and water quality problems would be eliminated. The result of this type of change would appear to be much more beneficial than detrimental to the economy of the region. More specific results to the water resources system are shown in the speculation impact matrices shown in Tables 21 and 22 in the Appendix.

REGION 12 - TEXAS-GULF REGION

The Texas-Gulf Region includes 173,000 square miles, 94 percent of which is located in the state of Texas (Figure 42). Smaller amounts are in New Mexico (5 percent) and Louisiana (1 percent). The region is quite diverse, extending from the semi-arid high plains to the humid Gulf Coast. With the exception of El Paso, the region includes the major metropolitan areas in Texas.

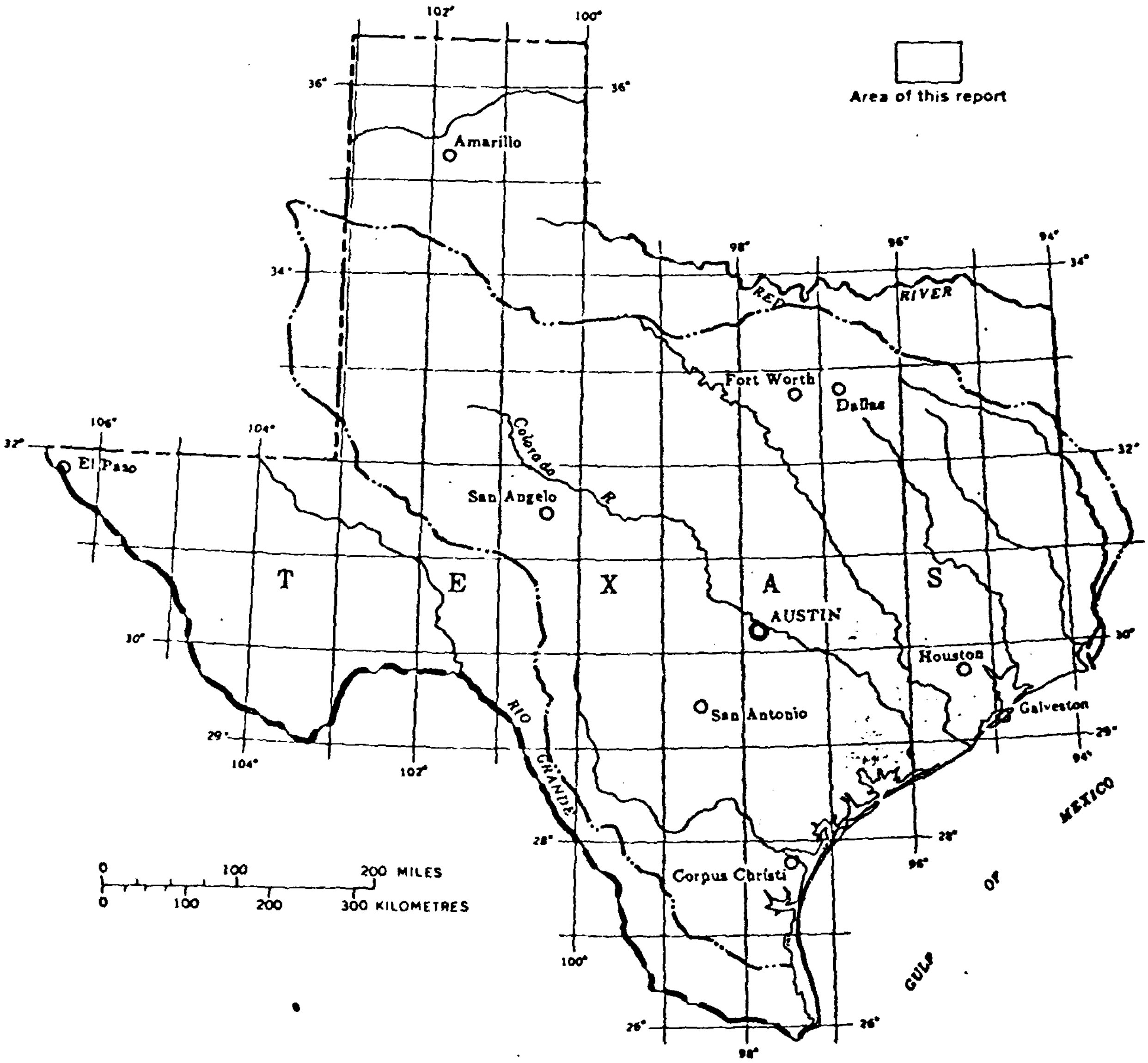


Figure 42. Location and drainage of the Texas-Gulf Region

The climate is as diverse as the landscape. Annual precipitation averages from 12 inches along the western edge of the high plains to 56 inches along the upper coast of the Gulf of Mexico. Precipiation increases uniformly from west to east in the mid-part of the region, averaging about 1 inch for each 15 miles distance. Convective thunderstorms provide most of the moisture in the west. These are often high intensity, short duration storms that produce considerable runoff. Tropical disturbances during the late summer and fall frequently produce torrential rains in coastal areas and inland to the Balcones uplift.

Hot summers and mild winters are characteristic features of the region although most sections are subject to rapid changes as cold Canadian air frequently penetrates into the area causing precipitous drops in temperatures during the winter months. Mean annual temperatures range from about 58°F. in the High Plains area to 74°F. in the extreme eastern part.

The native vegetation of the area ranges from short grasses in the semi-arid High Plains, to scrub oak and cedar on the Edwards Plateau, prairie grasses on the Upper Coastal Plain, to dense forests of pine (uplands) and hardwoods (bottomlands) on the Lower Coastal Plain.

As of 1975, the major land use within the region was for agriculture with 55 percent used for range and pasture and 22 percent for cropland. Forest and woodland (largely in east Texas) accounted for 18 percent and urban and built up areas were about 6 percent.

By the year 2000, the total agricultural land use is expected to decline by 2 percent. Largest changes will be in range land but cropland and irrigated farmland is also expected to decrease.

The western edge of this region lies along the High Plains where the predominant rock unit is the Ogallala Formation (Pleistocene) composed of sand, gravel, clay and silt. In some places, wind blown sand of Quaternary age overlies the Ogallala. East of the High Plains, in the Osage Plains, Permian red beds of sandstone and shale crop out. Eastward, these rocks grade into sandstone, shale and coal (lignite) of Pennsylvanian age that are overlain by limestone of Cretaceous age forming the Edwards Plateau. South and east of the Edwards Plateau, the region is underlain by younger Cretaceous units of claystone and limestone and transected by the Balcones and Mexia-Luling Fault Zones. Precambrian igneous and metamorphic rocks crop out in the central part of the region. In much of the eastern part of the region, the Cretaceous rocks are overlain by thick sequences of sediments dipping toward the southeast. These units include the Midway Groups (clay and sand), the Wilcox and Clairborne Group (sand, clay, silt, lignite), and Jackson Group and Catahoula Formation (sand, clay, silt, volcanic ash, lignite) and the upper most Fleming Formation (clay).

Ground water in the Texas-Gulf Region is a large and important resource that provides a significant percentage of the total water supply. About one-half of the present water supply is from ground water but this is expected to decrease appreciably by the year 2020 (Figure 43). An estimated 1.04 billion

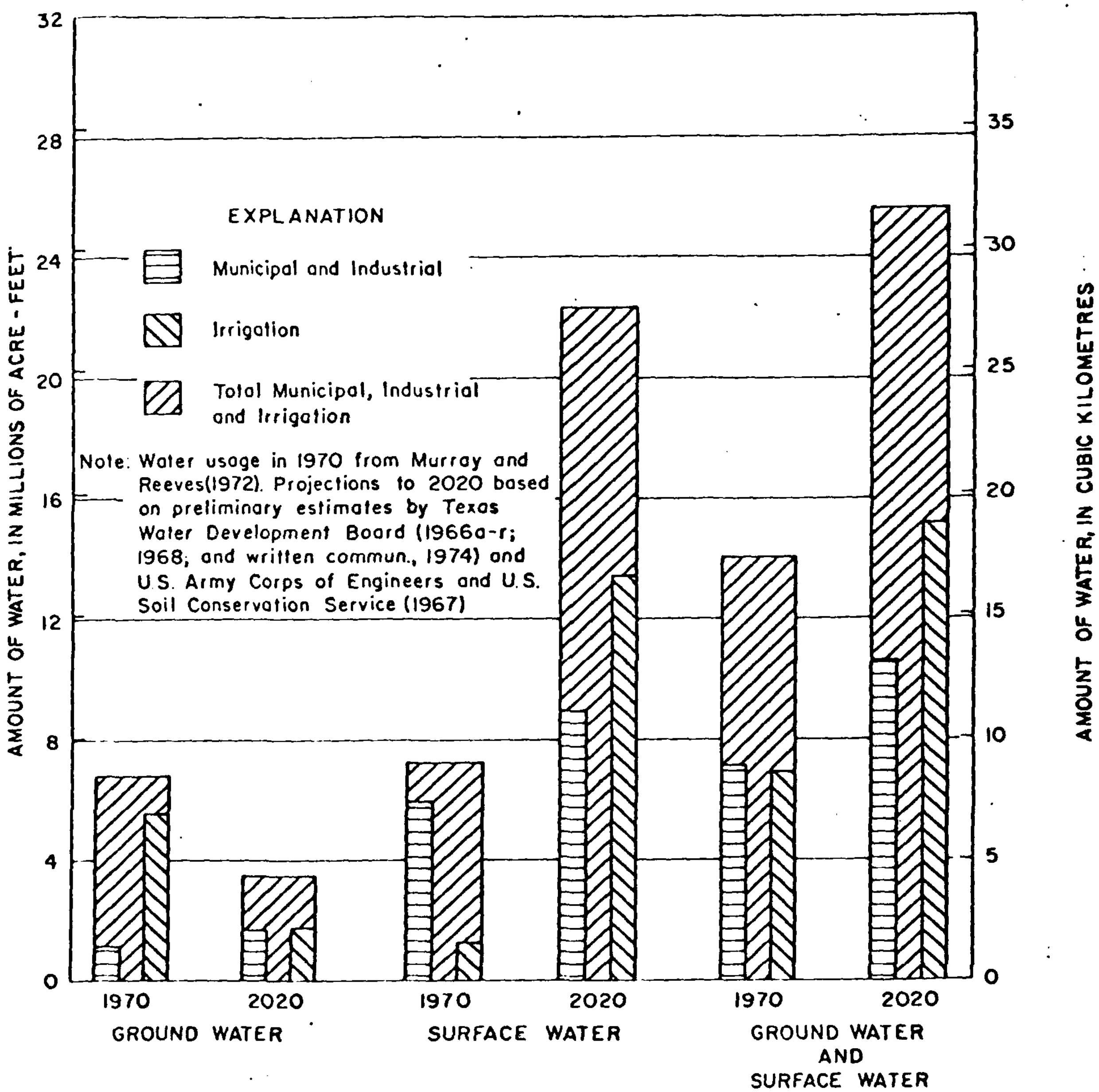


Figure 43. Present use of water in the Texas-Gulf Region by source - ground water and surface water - and projected use through the year 2020.

acre-feet of recoverable water is in streams above a depth of 400 feet and 3.3 billion acre-feet is recoverable from below that depth (Baker and Wall, 1976). But it is estimated that half of this water in storage will be depleted within 350 years at the present rate of withdrawal.

Most of the ground water storage in the region is contained in seven major aquifers as shown by Figure 44. There also are several minor aquifers within the region but their contribution is relatively small. All of those in the western part of the region are water-table aquifers while the larger leaky artesian system aquifer along the coast is presently subsiding and faulting because of heavy pumpage. Saltwater intrusion is also a major problem in the coastal section. All of the aquifers are recharged primarily by precipitation but only a fraction of that falling on the recarge zones is recharged. Ground water from the Ogallala Formation is the predominant source of water for the High Plains area (northwestern corner of the region). The Ogallala does not receive appreciable recharge. Average water level decline in this aquifer is about 3.5 feet per year. At this rate, it is expected that all available water will be withdrawn from the Ogallala Formation in the next 30 to 50 years.

Land subsidence is a very serious problem within the Houston-Galveston area, and has exceeded one foot in an area of about 2,500 square miles. Activation of faults in the Houston-Galveston area is another serious problem and is correlated to land subsidence. More than three feet of displacement has occurred along the Long Point Fault in western Houston. This subsidence will increase flood damages as more land is subject to surging tides and tropical storms along the coast. A number of underground water conservation districts have been formed, to encourage and implement more efficient use of ground water.

Mean annual streamflow from the region is estimated to be 28.3 bgd (31.7 maf). The median is estimated at 22.9 bgd (25.7 maf) indicating a moderate skewness in the distribution of flow. The 95 percent exceedence flow is 6.3 bgd (7.06 maf) and the 5 percent exceedence is 62.4 bgd (69.9 maf). Q_{05}/Q_{95} is 9.9. Total annual runoff from this region is estimated to be 35.63 bgd (39.9 maf) and ground water mined is estimated to be 5.58 bgd (6.25 maf). Consumption of water within the region is estimated to be 11.26 bgd (12.61 maf) and losses to evaporation are estimated to be 1.70 bgd (1.90 maf). The U.S. Fish and Wildlife Service estimates that 22.92 bgd (25.67 maf) of streamflow is necessary for optimal fish and wildlife habitat conditions.

Although there appears to be large variance in the monthly flows over the region, extreme low flows tend to occur most often in the spring. Runoff is lowest in relation to total area drained in the southern and western portions of the region. In the eastern part, low flows occur during July-November and high flows during December-June with May being the peak flow month. Each month shows slight to moderate skewness of the distribution of flows. In the central part of the region, flows can be high from October-June, with June being the peak flow month. Low flow occurs during August and September. The distribution of flows within each month is highly skewed

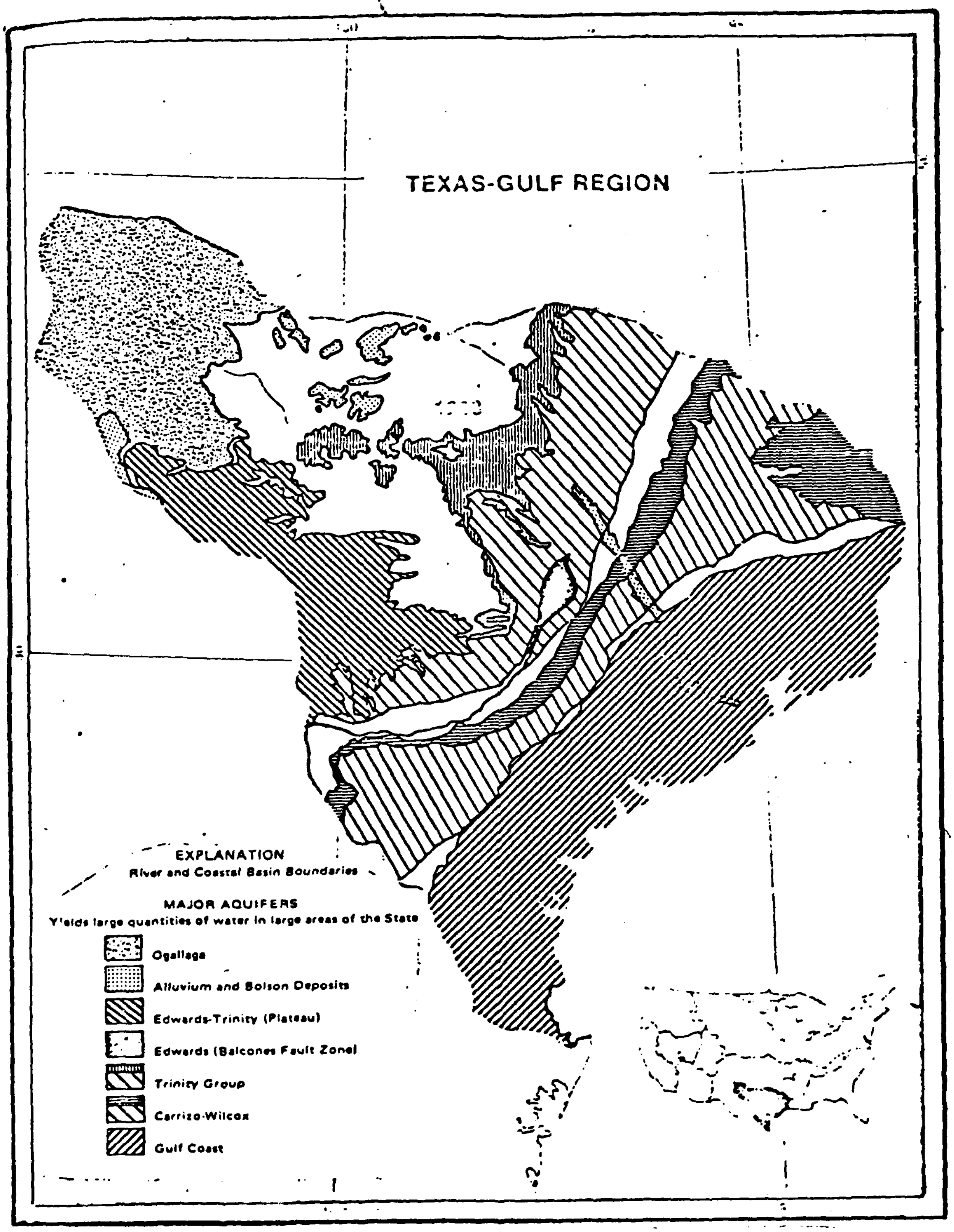


Figure 44. Distribution of major aquifers in the Texas-Gulf Region.

toward the right. In the southwestern part of the region peak flows occur three times during a typical year, in May, July and September. Typical low flow months are November-April of each year. Analysis of the data from all areas in the region show insignificant trends for the period 1925-1976.

Present withdrawals in the region amount to 16.92 bgd (18.95 maf) of which 68 percent is used for irrigation, 11 percent for manufacturing and 7 percent for domestic purposes. By the year 2000, this is expected to rise to 15.54 bgd (17.40 maf), of which 48 percent will be for irrigation, 16 percent for manufacturing, 15 percent for steam-electric generators, 10 percent will be for domestic and 8 percent for mineral processing. In 1975 ground water supplied 68 percent of the total withdrawals and surface water 32 percent but ground water supplies are diminishing rapidly because pumpage exceeds recharge by a big margin. Therefore, the region must become more dependent upon surface water supplies to meet the projected year 2000 requirements. By the year 2000, it is estimated that ground water will supply on 19 percent of the total needed and surface water will make up the remaining 81 percent.

Surface water storage capacity in this region is not especially large. Normal storage capacity is 7,660 bg (23.40 maf) and flood storage capacity is 17,912 bg (54.95 maf). Flooding is a common problem in the region and because of the wide variation in climate and physiography the magnitude and character of floods differ widely both within and among the major river basins. Hurricane related flooding has been responsible for most of the extreme floods that have occurred in the region.

Heavy industrialization and population increases have resulted in steadily rising water requirements for the large cities of the region. These cities depend predominantly on surface water supplies from nearby reservoirs. These existing supplies will not be able to satisfy forecasted water requirements to the year 2000, unless additional reservoirs are constructed.

Climatic data from weather stations at Houston, Fort Worth and San Antonio have been used to construct the climatic scenarios. The ratios of estimated mean annual runoff due to climatic change to the present runoff is shown in Table 16 for each of the four scenarios.

Scenario	Southeast	North Central	Southeast	Average
1 (warmer and drier)	.60	.50	.40	.50
2 (cooler and wetter)	1.65	2.00	2.00	1.88
3 (warmer and wetter)	.76	1.37	1.00	1.03
4 (cooler and drier)	.94	1.00	1.00	.98

Table 16. Estimated ratio of total annual runoff under the assumption of climatic change to that of present runoff for the Texas-Gulf Region.

Scenario	Ratio $\overline{Q}$ scenario/$\overline{Q}$ present
1 (warmer and drier)	.50
2 (cooler and wetter)	2.00
3 (warmer and wetter)	1.17
4 (cooler and drier)	1.00

Table 17. Estimated ratio of mean annual total runoff under climatic change to the present mean annual runoff based on regional average temperature and precipitation.

As in the Missouri River Region, the climatic change scenarios have been appraised both by looking at individual station changes (Table 16) and by evaluating the effect on the regional average temperature and precipitation changes (Table 17). As in the other case, the differences are small and only scenarios 1 and 2 appear to be significant on a region-wide basis.

Scenario 1 (warmer and drier) would reduce the present runoff by about 50 percent. There is little doubt that the results would be disastrous. The annual runoff would be reduced to 17.8 bgd (19.9 maf) just slightly above the present total withdrawal rate 16.9 bgd (18.9 maf) and relatively close to the total consumption rate of 11.3 bgd (12.7 maf). Recharge to aquifers would no doubt be reduced considerably and with the decline of surface water supplies, ground water pumpage would increase considerably. Thus, it is estimated that region-wide water shortages would exist, salinity of surface water would increase and mining of ground water (with accompanying mining subsidence, faulting and salt water intrusion) would become more intense.

If a scenario 2 (cooler and wetter) type change would occur, the present mean annual runoff from the region would be doubled and provide 71.3 bgd (79.9 maf). The results would be mostly beneficial. Agriculture would benefit considerably. Ground water use would decline and surface water supply would be greatly incresed. Flooding would occur in low lying areas. Tables 23 and 24 in the Appendix outline in more detail the speculated impacts of climatic change scenarios 1 and 2.

REGION 13 - RIO GRANDE REGION

The location and extent of the Rio Grande Region is shown on Figure 45. It includes that part of the Rio Grande River Basin that lies within the United States. Most of the region is in New Mexico (54 percent), 40 percent is in Texas and 6 percent in Colorado. The total drainage area of the Rio Grande is 230,000 square miles; 93,000 square miles of the total is in Mexico. Only 89,000 of the 137,000 square miles in the USA contributes runoff to the river as 44,000 square miles drain into closed basins. The Rio Grande forms the border between the United States and Mexico for 1,244 miles, essentially between El Paso and Brownsville, Texas. Thus management of the water resources in the region have international implications. Treaties regulating water use were entered in 1906 and later in 1933 and 1944. Their execution is the responsibility of the International Boundary and Water Commission.

The generally arid climate of the region is characterized by low humidity and erratic rainfall. Average annual precipitation ranges from 30 inches in both the high mountains of the headwaters and the Gulf Coastal Plain to about 8 inches in the central portion. Although total precipitation over the area averages 86 million acre-feet, its variability, coupled with high evapotranspiration rates and the recurrence of prolonged dry periods, creates major water problems.

Temperatures over the region vary from quite harsh in the mountains to very mild in the lower portions of the valley. Mean annual temperatures vary from 40°F. to 74°F. from the higher mountains to areas near the Gulf of Mexico.

Livestock grazing is the dominant land use with more than 72 percent of the area used for pasture and range. Forests and grazed woodlands comprise 17 percent of the total use, while 3.3 percent is cropland. Essentially all of the 2 million acres in cultivation is irrigated. Less than 1 percent of the land is in urban and built-up areas; partks, military bases and reservations, wildlife refuges, water resource developments, etc. make up almost 6 percent. Most of the 15 million acres of forest is in the mountainous area of New Mexico.

From the headwaters of the Rio Grande in southern Colorado to the vicinity of El Paso, Texas, the main stem drainage basin is associated with a rift-zone valley, or crustal break, and flanking mountain ranges. The rift-zone consists of a chain of grabens or structural basins in which enormous thicknesses of alluvial valley fill and local lava flows have accumulated. From El Paso downstream to the vicinity of Big Bend National Park, the basin is in a region of fault-block mountain ranges and intervening intermontane basins. On the valley slopes and in the valley proper, considerable thicknesses of alluvial outwash and valley fill have accumulated. From Big Bend National Park to the Lower Rio Grande Valley, the basin crosses essentially flat-lying consolidated sedimentary rocks predominantly of limestone, shale, and sandstone. In the Lower Rio Grande Valley,

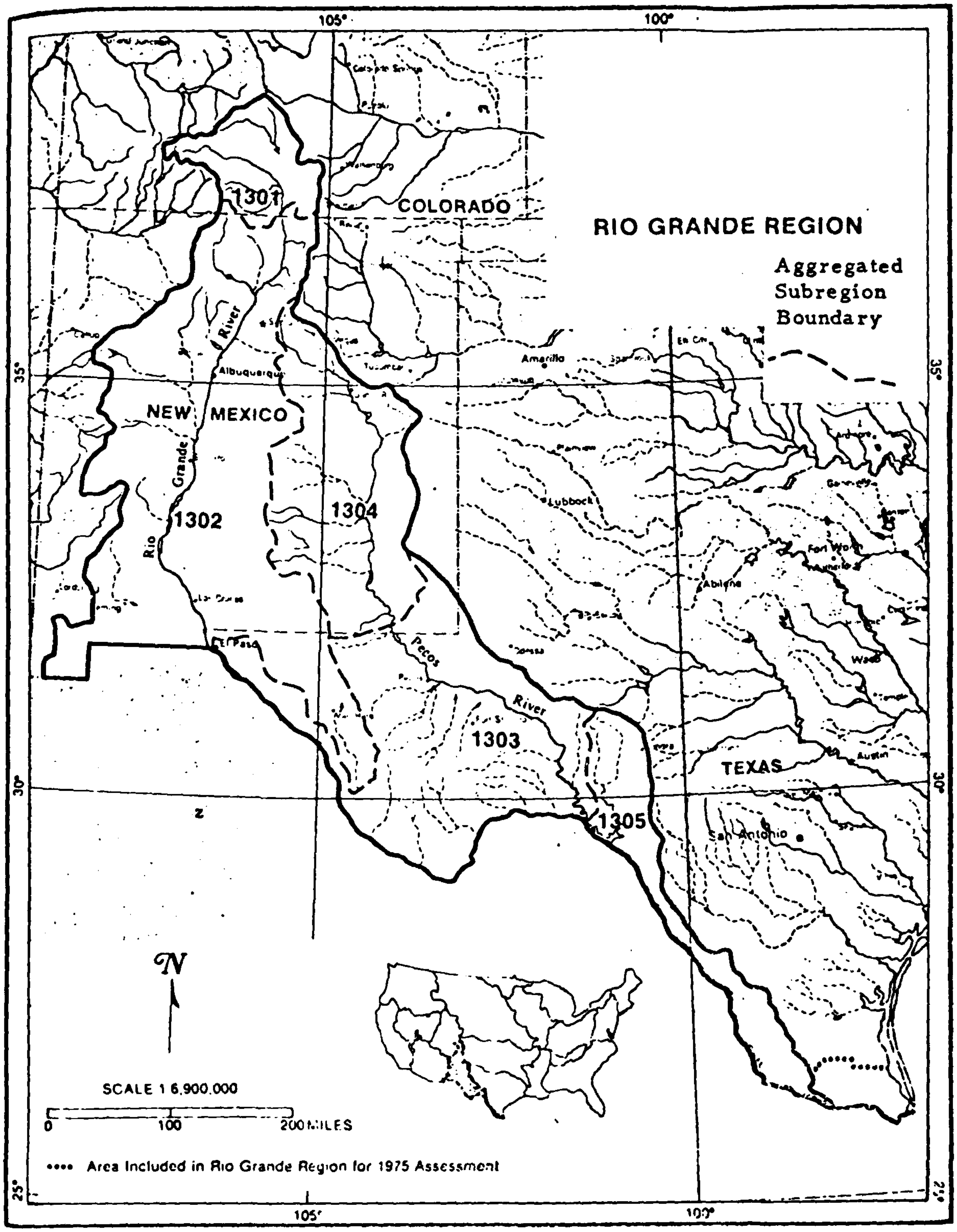


Figure 45. Location and drainage of the Rio Grande Region

alluvium underlies the basin and makes up terraces and the river's delta. Limestone, sandstone, shale, gypsum, and salt underlie the Pecos River Basin. Locally, as in the Roswell-Artesia area and near the New Mexico-Texas state line, there are notable accumulations of alluvial and eolian valley fill.

The alluvial valley fill in the upper and middle main stem of the Rio Grande Basin constitutes the major fresh-water aquifer. Locally in New Mexico the valley fill is reported to be as much as 9,000 feet in thickness, and up to 30,000 feet in thickness in the San Luis Valley in southern Colorado. Between Big Bend National Park and the Lower Rio Grande Valley, consolidated sedimentary rocks of limestone and sandstone are highly variable but locally quite productive. In the Lower Rio Grande Valley, the alluvium in the Rio Grande delta is an erratic but locally productive aquifer. In the Pecos River Basin, beds of solutioned limestone and gypsum constitute productive aquifers; however, much of the groundwater contains considerable quantities of dissolved solids. Where the alluvial valley fill is thickest, it is a significant aquifer along the Pecos River. Distribution of the aquifers is shown in Figure 46.

Ground water reservoirs in the region have been estimated to contain an aggregate of more than 5.8 billion acre-feet of fresh to slightly saline water in storage. Presently the total withdrawals from the ground water reservoirs is estimated to be 2.3 bgd (2.6 maf) of which 0.7 bgd is being mined. The major part of the ground water withdrawals are for irrigation (88 percent), of which 53 percent was consumed and 47 percent returned to streams or ground water reservoirs.

Diversion of water from the Rio Grande occurred prior to European settlements and reached significant amounts before systematic streamflow measurements were initiated. Thus no actual measurements of natural flow are available and those that follow are strictly hydrologic estimates based on the best available data. Their reliability may be questioned due to incomplete knowledge of depletions in Mexico.

The mean annual streamflow from the region has been estimated as 1.2 bgd (1.34 maf) at the mouth of the river near Brownsville, Texas. The distribution of flow is highly skewed as the median of the annual runoff series is only 0.6 bgd (4.92 maf) and the 90 percent exceedence flow is only 0.2 bgd (0.22 maf). Q_{05}/Q_{95} is 22.0.

The estimated annual runoff is 5.31 bgd (5.95 maf) and 2.34 bgd (2.62 maf) is imported from outside the basin. Currently ground water is being mined at a rate of 0.66 bgd (0.74 maf) per year.

Total annual fresh water withdrawals are estimated to be 6.32 bgd (7.08 maf) as of 1975 but this is expected to decline to 5.63 bgd (6.31 maf) by the year 2000. In 1975, 5.24 bgd (5.87 maf) of the total withdrawals were consumed; by the year 2000, this volume is expected to decrease slightly to 4.02 bgd (4.50 maf) annually.

In the northern part of the region, the runoff comes primarily from

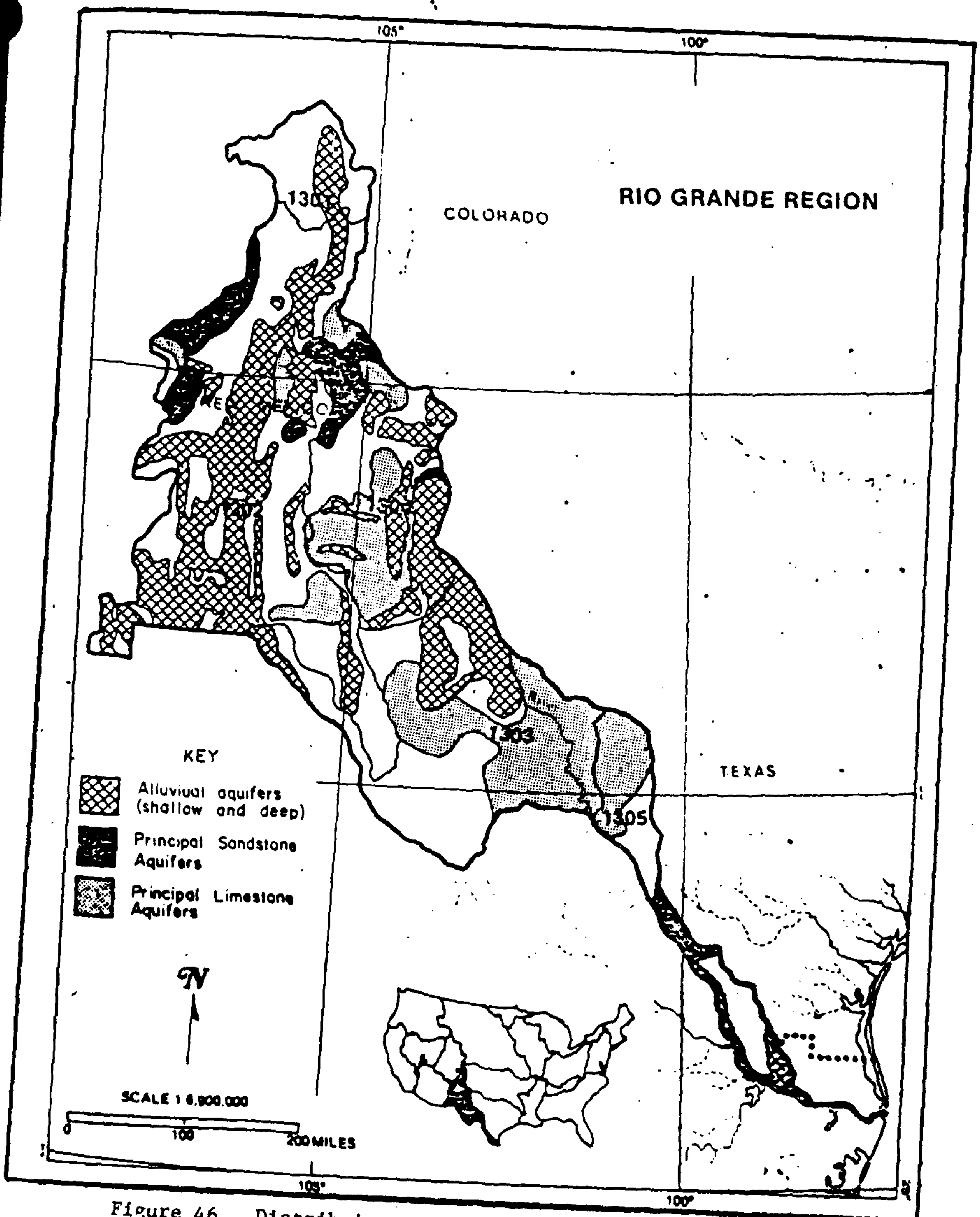


Figure 46. Distribuiton of the major aquifers in the Rio Grande Region.

snowmelt with maximum amounts in May and June. During the remaining months, there is little to no flow. The distribution of flow is highly skewed in all months with low flows highly predominant. Runoff is also generated from late summer-early fall rains in the central part of the region. Thus, the high flow months are April-September with little to no flow during the remaining months. The data are not highly skewed as in the northern part. In the lower part of the region, the high flow months are September and October with little flow occurring during the remaining months. This peak flow is probably related to tropical weather disturbances that develop off the coast in the Gulf of Mexico during this part of the year. These disturbances often reach hurricane strength and cause severe flooding in the lower valley.

The runoff data show significant downward trends throughout the region. The trend is estimated to be -0.642 percent per year (for the period 1900-1976) for the central part. From the upper Pecos River (the major tributary of the Rio Grande), the rate of decrease is -4.089 percent per year but this is for a shorter period, 1938-1976. In the lower portion of the region, the trend is -3.593 percent per year for the period 1900-1976. Obviously, if this rate continues, in 28 years the amount of runoff from the region will decrease by 100 percent.

Reservoir storage capacity in the region is 2,534 bg (7.77 maf) and flood storage capacity is 4,410 bg (13.53 maf). Although flooding is not a universal problem in the region it does occur frequently as the result of high runoff from intense thunderstorms that characterize the arid climate during the summer. Flooding is frequently severe in the lower valley as large amounts of rainfall are dumped on the area when tropical storms move in from the Gulf of Mexico. Poor drainage conditions in the low-lying land aggravate the situation during major storms.

Several important points must be kept in mind considering streamflow as a source of water within the region; 1) there is no surplus water in the region either for new use or expanding those already in existence; 2) the states within the region have developed legal institutions for the allocation and administration of water and these are legally enforced; 3) the Rio Grande is an international river and decisions must be made on this basis; 4) there are unsolved Indian Rights problems; and 5) the generally arid climate requires conservation of existing supplies to meet regional water needs and requirements.

Because of the aridity of most of the region, it is extremely difficult to estimate the effects of the postulated climate changes. However, because a large percentage of the runoff comes from snowmelt, stations in the upper part of the basin were used. These stations are Santa Fe, New Mexico and Hermit Lake, Colorado. Monthly precipitation and temperature records were used to estimate the ratio of change in annual runoff for the climatic change scenarios and the percent runoff (see Table 18). We have also computed the ratios for region wide average monthly precipitation and temperature (Table 19).

Scenario	Central	North	Average
1 (warmer and drier)	.25	.56	.45
2 (cooler and wetter)	1.25	1.56	1.45
3 (warmer and wetter)	1.00	1.00	1.00
4 (cooler and drier)	1.00	1.03	1.00

Table 18. Estimated ratio of $\overline{Q}$ scenario/$\overline{Q}$ present for mean annual flows in the Rio Grande Region.

Scenario	Ratio of $\overline{Q}$ scenario/$\overline{Q}$ present
1 (warmer and drier)	.24
2 (cooler and wetter)	1.80
3 (warmer and wetter)	1.00
4 (cooler and drier)	1.00

Table 19. Estimated ratio of $\overline{Q}$ scenario/$\overline{Q}$ present for annual flows but based on regional averages of temperature and precipitation.

Because of large areas not covered by the two stations used in Table 18, the values based on the regional averages (Table 19) appear to be a better estimate although they are not grossly different from the values based on the station data.

The occurrence of postulated climatic changes, as in scenario 1 (warmer and drier), would reduce the mean annual runoff to an estimated 24 percent of the present amount. This would amount to an annual runoff of about 1.5 maf per year. There is little doubt, given the present maximum use of water in the region, that such an extreme reduction in runoff would cause tremendous economic and legal problems within the region. Since irrigated agriculture uses the largest portion of the water, this sector of the economy would be the most severely affected. There would be a decline in both stored surface water and ground water recharge. Use of ground water would increase many times. The present water supply is already intensively used and additional shortages would greatly increase the demand to a critical point.

If a climatic change as postulated in scenario 2 (cooler and wetter) would occur, it is estimated that the mean annual runoff within the region would be increased 1.80 times. Thus, the mean annual runoff with the region would be boosted to an estimated 10.7 maf per year. Obviously, this type of change would greatly benefit the economy of the region and solve many of the currently pressing legal problems associated with water use in the region although flood storage and control might prove to be inadequate.

An evaluation of the effects in water supply of the occurrence of the two scenarios 1 and 2 (3 and 4 appear to be less significant) are included in Tables 25 and 26 in the Appendix.

REGION 14 - UPPER COLORADO REGION

The Upper Colorado Region covers about 113,500 square miles and includes parts of Arizona, Colorado, New Mexico, Utah and Wyoming (Figure 47). It extends from the Rocky Mountain divide in Colorado, west to the Wasatch Mountains in Utah and from the Wind River Mountains of Wyoming, south to the high deserts in northeast Arizona and northwest New Mexico. The region encompasses high mountains and plateaus, narrow valleys and broad expanses of desert. This diverse landscape has produced many areas of great scenic beauty and numerous unique natural areas. Because of these attributes many areas have been set aside as wilderness. Nine such areas (1.35 million acres) have been established and 84 other areas (1.6 million acres) are being considered for the National Wilderness System.

The overall climate of the region is semi-arid to arid. Precipitation, however, exceeds 40 inches in the higher mountains but reaches a low of 6 inches in the desert areas. Most agricultural areas receive from 10 to 20 inches which occurs as snow in the winter and rain in the spring. Summers are dry and clear, sunny days are dominant in most parts of the region throughout the year. Mean annual temperatures range from less than 30°F. in the high mountains to 50°F. in the south-central sections. Temperature extremes range from sub-zero to over 100°F.

Range, pasture and other agricutural uses occupy about 54 percent of the land. Another 3 percent is in irrigated croplands. Forests occupy about 27 percent, urban developments less than 1 percent, and about 15 percent in other uses. Forest land owned by the Bureau of Land Management is included in the latter category along with other miscellaneous uses.

The rock types of almost all ages (except perhaps Precambrian) serve as aquifers in the Upper Colorado Region. Price and Arnow (1974) after Irons and others (1965) listed the major aquifers by physiographic provinces within the region. The list is shown in Table 20.

Presently comparatively little of the water consumed within this region is produced from ground water (Figure 48). In the future, because of legal constraints and shortage of surface water supplies, greater usage of the ground water is expected.

The annual mean streamflow from the region is 10.0 bgd (11.20 maf) and the median is the same. Therefore, the distribution of below average flows is equal to the above average flows. The 5 percent exceedence flow is 15.6 bgd (17.47 maf) and the 95 percent exceedence flow is 3.9 bgd (4.37 maf). Q_{05}/Q_{95} is 4.0.

The estimate of the mean annual runoff is uncertain. Within the WRC (1978) publication, three estimates are given: 12.4 bgd (13.9 maf), 13.96 bgd (15.64 maf), and 13.39 bgd (15.00 maf).

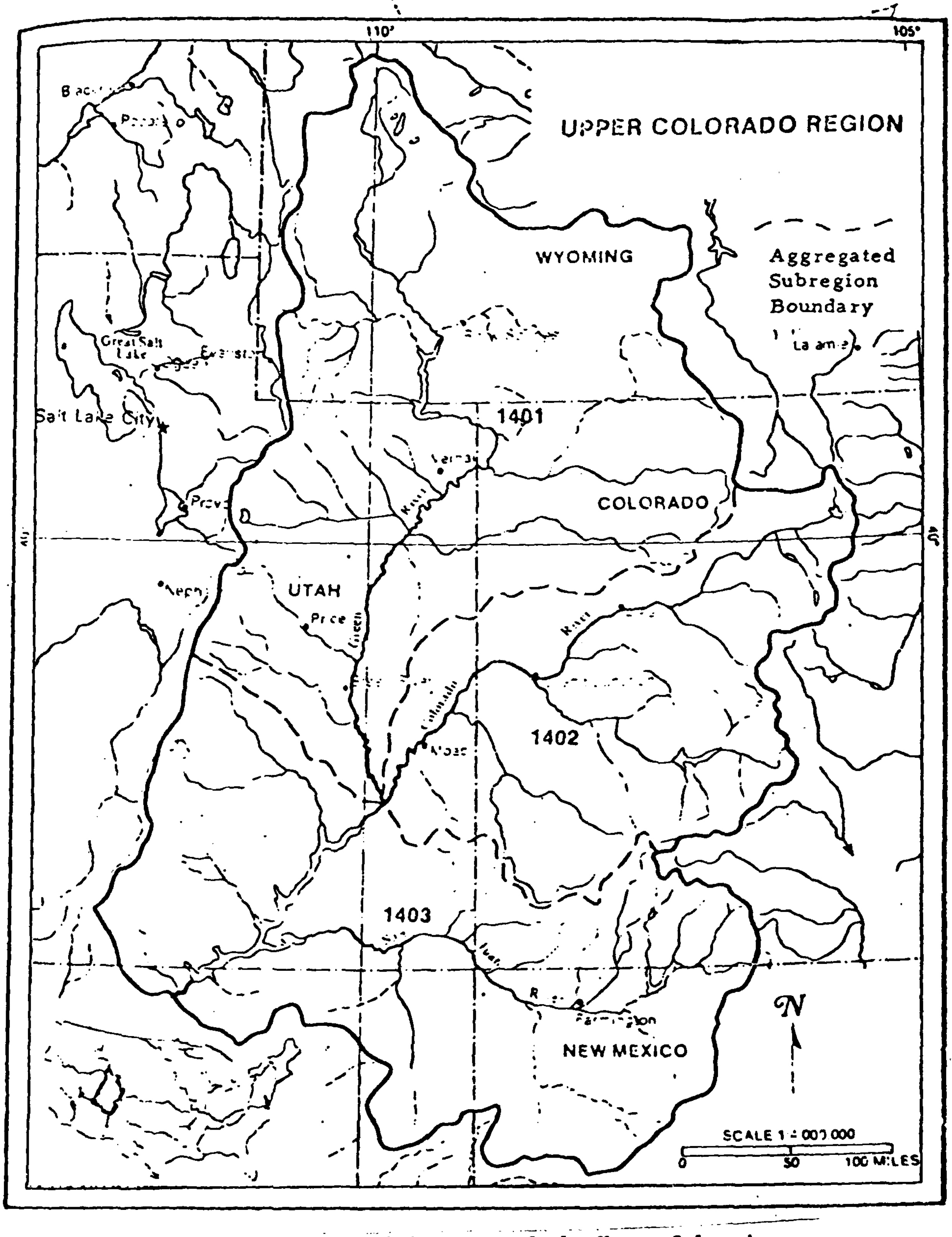


Figure 47. Location and drainage of the Upper Colorado Region

WYOMING BASIN PROVINCE

A - West-central part of Green River Basin

- Quaternary
  - Unconsolidated sedimentary deposits (mostly alluvial and lacustrine in origin)
- Tertiary
  - Bridger Formation
  - Green River Formation
  - Wasatch Formation
- Jurassic
  - Nugget Sandstone
- Ordovician
  - Bighorn Dolomite

B - Great Divide and Washakie Basins

- Quaternary
  - Unconsolidated sedimentary deposits (mostly alluvial and lacustrine in origin)
- Tertiary
  - Brown Park Formation
  - Green River Formation
  - Wasatch Formation-Battle Spring Formation
- Cretaceous
  - Ericson Formation
  - Rock Springs Formation
  - Mesaverde Formation (east part of area)
- Mississippian
  - Madison Limestone

MIDDLE ROCKY MOUNTAINS PROVINCE

C - South flank of Uinta Mountains

- Quaternary
  - Unconsolidated sedimentary deposits (mostly alluvium)
- Cretaceous
  - Dakota Sandstone
- Jurassic
  - Nugget Sandstone
- Permian
  - Park City Formation
- Pennsylvanian
  - Weber Quartzite
  - Morgan Formation

UINTA BASIN SECTION

D - Eastern and central parts

- Quaternary
  - Unconsolidated sedimentary deposits (mostly alluvium)
- Tertiary
  - Duchesne River Formation
  - Uinta Formation
  - Green River Formation
  - Wasatch Formation
- Cretaceous
  - Frontier Sandstone Member of Mancos Shale
  - Mowry Shale
  - Dakota Sandstone
- Triassic (?) and Jurassic
  - Glen Canyon Sandstone
- Permian
  - Park City Formation
  - Phosphoria Formation
- Pennsylvanian
  - Weber Sandstone (Quartzite)
  - Morgan Formation
  - Round Valley Limestone

HIGH PLATEAUS OF UTAH

E - Northern part

- Quaternary
  - Unconsolidated sedimentary deposits (mostly alluvium)
- Tertiary
  - Crazy Hollow Formation
  - Flagstaff Formation
- Cretaceous and Tertiary
  - North Horn Formation
- Cretaceous
  - Emery Sandstone Member of Mancos Shale
  - Ferron Sandstone Member of Mancos Shale
- Jurassic
  - Carmel Formation
- Triassic (?) and Jurassic
  - Navajo Sandstone (Glen Canyon Group)
- Triassic
  - Wingate Sandstone (Glen Canyon Group)

F - Southern Part

- Quaternary
  - Unconsolidated alluvial and lacustrine deposits (probably some extrusive igneous rocks)
- Tertiary
  - Igneous rocks
  - Brian Head Formation
  - Wasatch Formation
- Cretaceous
  - Kaiparowits Formation
  - Wahweap Sandstone
  - Straight Cliffs Sandstone
- Jurassic
  - Carmel Formation
- Triassic (?) and Jurassic
  - Navajo Sandstone (Glen Canyon Group)
- Triassic
  - Wingate Sandstone (Glen Canyon Group)

CANYON LANDS

G - Henry Mountains vicinity

- Quaternary
  - Unconsolidated sedimentary deposits (mostly alluvium and dune sand)
- Cretaceous
  - Dakota Sandstone
- Triassic (?) and Jurassic
  - Navajo Sandstone (Glen Canyon Group)
- Triassic
  - Wingate Sandstone (Glen Canyon Group)

H - La Sal Mountains vicinity

- Quaternary
  - Unconsolidated sedimentary deposits (mostly alluvium and dune sand)
- Cretaceous
  - Dakota Sandstone
  - Burro Canyon Formation
- Jurassic
  - Entrada Sandstone
- Triassic (?) and Jurassic
  - Navajo Sandstone (Glen Canyon Group)
- Triassic
  - Wingate Sandstone (Glen Canyon Group)
- Permian
  - Cutler Formation

NAVAJO SECTION

I - North-central Part

- Quaternary
  - Unconsolidated alluvium and dune sand (some igneous rocks)
- Tertiary
  - Chuska Sandstone
- Cretaceous
  - Dakota Sandstone
- Jurassic
  - Recapture Shale
  - Member of Morrison Formation
  - Salt Wash Sandstone
  - Member of Morrison Formation
  - Summerville Formation
  - Cow Springs Sandstone
  - Bluff Sandstone
- Triassic (?) and Jurassic
  - Navajo Sandstone (Glen Canyon Group)
- Triassic (?)
  - Moenave Formation
- Triassic
  - Owl Rock Member of Chinle Formation
  - Shinarump Member of Chinle Formation
- Permian
  - Cedar Mesa Sandstone
  - Member of Cutler Formation

J - Northeast part

- Quaternary
  - Unconsolidated sedimentary deposits (mostly alluvium)
- Tertiary
  - San Jose Formation
- Cretaceous
  - Dakota Sandstone
- Jurassic
  - Entrada Sandstone

SOUTHERN ROCKY MOUNTAIN PROVINCE

K - North Park and Middle Park vicinity

- Quaternary
  - Unconsolidated sedimentary deposits (mostly alluvium and glacial deposits)

L - Glenwood Springs-McCoy vicinity

- Quaternary
  - Unconsolidated alluvium
- Mississippian
  - Leadville Limestone

Table 20. Major aquifers in the Upper Colorado Region by physiographic provinces (after Price and Arnow, 1974).

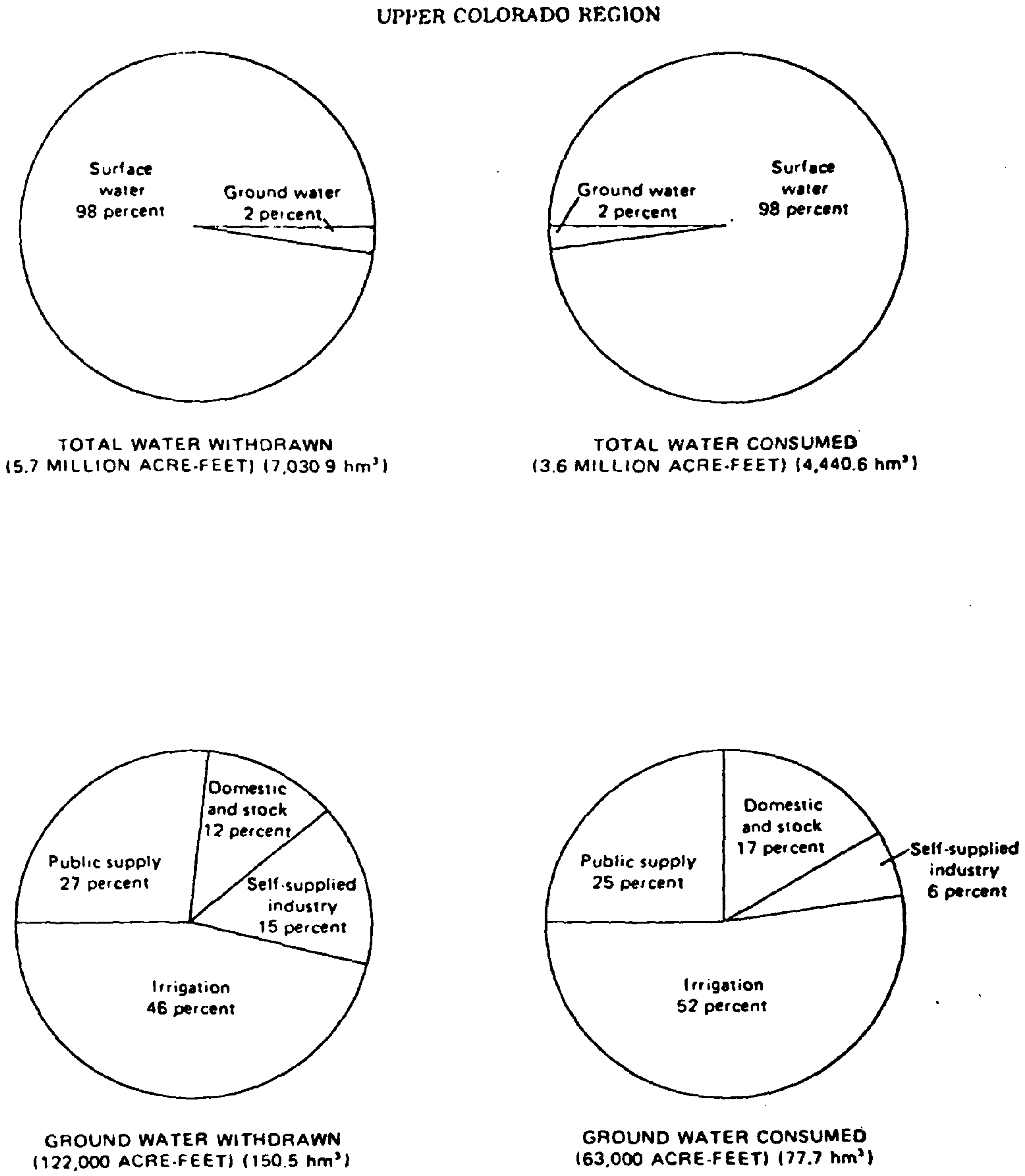


Figure 48. Source and use of water within the Upper Colorado River Region.

Total fresh water withdrawals for 1975 amounted to 6.87 bgd (7.69 maf) of which 2.44 bgd (2.73 maf) were consumed. By the year 2000, total withdrawals are estimated to be 7.52 bgd (8.42 maf) and the consumption 3.23 bgd (3.62 maf). Irrigation is the largest use; the present 93 percent is expected to be about 89 percent by 2000. Use for mining and processing minerals amounts to 2 percent but will rise to 5 percent by the year 2000. Domestic use is small (1 percent) and is expected to remain so. Total streamflow that is necessary for optimal fish and wildlife habitat conditions is 7.95 bgd (8.9 maf) per year.

As of 1975, evaporation losses amounted to 0.71 bgd (0.80 maf) per year and 0.80 bgd (0.90 maf) were exported from the basin. By the year 2000 these values are expected to rise to 0.73 bgd (0.82 maf) and 1.1 bgd (1.23 maf) respectively.

An estimated 85 percent of the total runoff from the region results from snowmelt in the higher mountain region. The peak runoff occurs in May and June; the remaining months being low flow months. Data for this type of runoff shows little to no skewness in the monthly distribution.

In the southern part of the region, rains occuring in July, August and September also produce significant runoff so that high flow months are April-September with low flows in the October-March period. The monthly distribution of flows from this part of the region are both more variable and less skewed (low flow predominant) than in the northern part of the region.

Flow records from all parts of the region show a significant downward trend from 1897-1976. The trend varies from -0.441 percent per year to -0.704 percent per year; the average is about -0.60 percent per year. Should this rate continue it is estimated that the flow would be completely diminished in 168 years but this is unlikely.

Normal surface water reservoir capacity in the region is 3,328 bg (10.2 maf) and flood storage capacity is 3,691 bg (11.32 maf). At the present, flooding is not considered a problem in the region. High salinity of the water creates problems for downstream agricultural uses.

Climatic data from Grand Junction, Colorado, Lander and Pinedale, Wyoming, and Grand Lake and Pagosa Springs, Colorado were assessed to evaluate the runoff ratios under the postulated climatic change scenarios and the present (Table 21). The regional wide averages of temperature and precipitation were also analyzed similarly and are shown in Table 22.

The occurrence of a climatic change similar to that described by scenario 1 (warmer and drier) would cause an estimated 35 percent decrease in runoff. Consequently, if the 15.00 maf estimate of current average annual runoff is accepted, the amount under scenario 1 would be reduced to about 9.75 maf. There would be a general decrease in firm reservoir yield as the mean flow becomes more variable and less persistent. Recharge to the major aquifers would decline with the decrease in direct surface runoff. However, ground water usage would increase, as would salinity in the rivers.

Scenario	Central Grd Junt	North Lander	North Pinedale	East Grd Lake	South Pagosa Spgs	Ave
1 (warmer and drier)	.50	.40	.21	.59	.50	.44
2 (cooler and wetter)	2.00	3.00	2.10	1.51	1.43	2.01
3 (warmer and wetter)	1.00	.40	.71	.95	.93	.80
4 (cooler and drier)	1.00	.40	2.10	1.09	.83	1.08

Table 21. Ratios of $\overline{Q}$ scenario/$\overline{Q}$ present for mean annual flow estimated from regional averages of temperature and precipitation in the Upper Colorado Region.

Scenario	Ratio of $\overline{Q}$ scenario/$\overline{Q}$ present
1 (warmer and drier)	.67
2 (cooler and wetter)	2.00
3 (warmer and wetter)	.67
4 (cooler and drier)	1.07

Table 22. Ratios of $\overline{Q}$ scenario/$\overline{Q}$ present for mean annual flows estimated from station data in the Upper Colorado River Region.

The capacity of the water system to respond would be poor as presently available water is over-appropriated. Obviously, there would not be enough water to fulfill the "Law of the River" and legal and economic disruption would ensue.

Under a scenario 2 (cooler and wetter) climatic change the percent annual runoff would increase an estimated 2.0 times. The current estimate of 15.0 maf per year would increase to 30.0 maf and enough water would be available to fulfill all the present and anticipated future demands on the river. Pressure for increased exports would follow and some flooding would occur as present flood control structures would be inadequate.

The occurrence of a scenario 3 (warmer and wetter) climatic change would be significant and the results would be similar to those of scenario 1 (warmer and drier). The occurrence of a scenario 4 (cooler and drier) would be trivial.

The speculated impacts of climatic change similar to those described by scenarios 1 and 2 on the water resources system of the region are shown in Tables 27 and 28 in the Appendix.

REGION 15 - LOWER COLORADO REGION

The region defined as the Lower Colorado River Region by the WRC -- with the exception of a small area in southern California -- is hydrologically identical to the drainage basin of the Colorado River below Lees Ferry, Arizona (Figure 49). Most of the region is in Arizona (73 percent), with smaller portions in the state of New Mexico (13 percent), Nevada (12 percent), Utah (2 percent) and California (2 percent). Total area is 154,859 square miles.

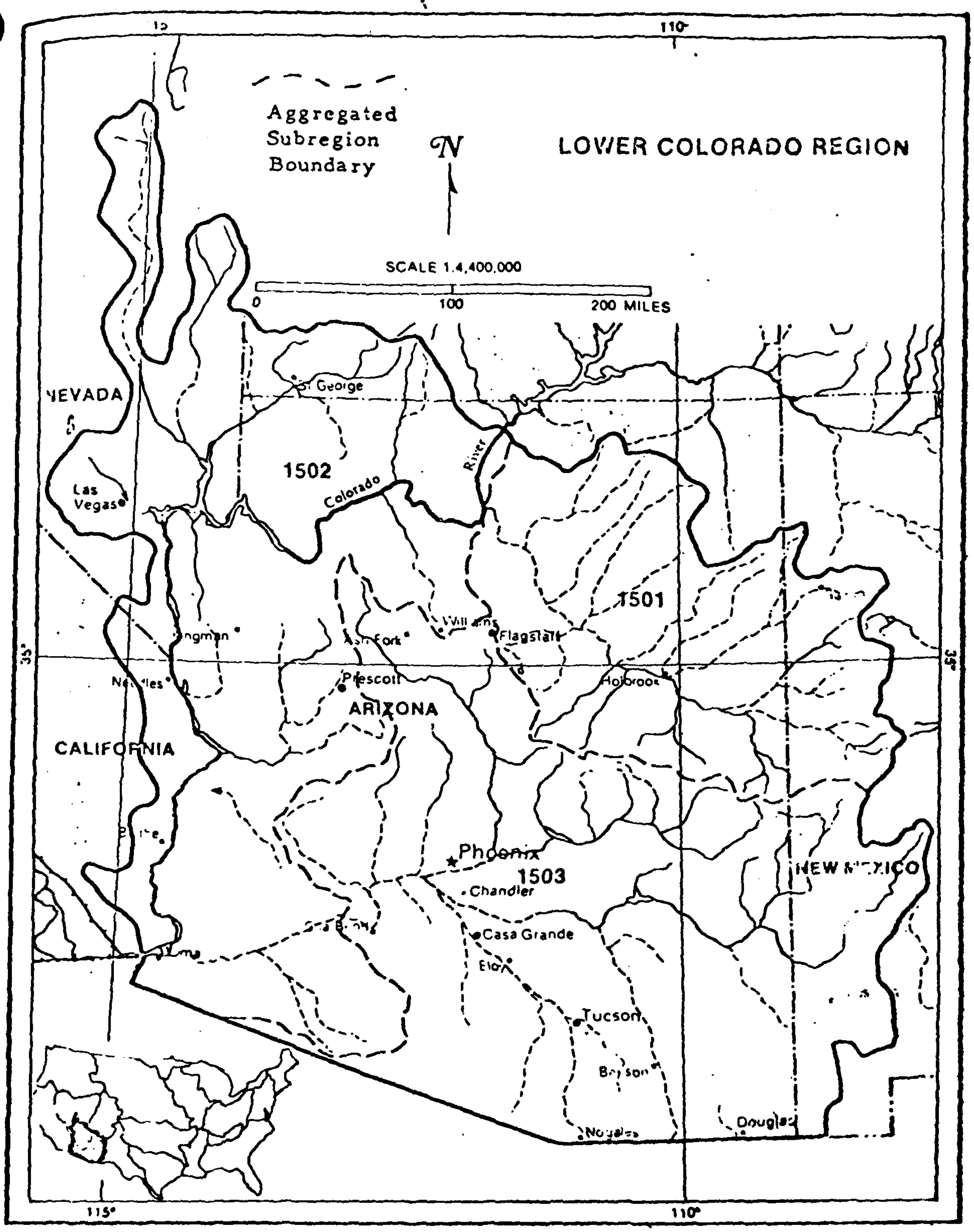
The Colorado River System is unique in many ways. In spite of a relatively low flow, when compared to other major rivers, a higher percentage of water is exported from its system than from any other river in the United States. In fact, over half the west, including major metropolitan areas in southern California and central Arizona are supplied at least in part by water from the Colorado River.

The natural vegetation in the area includes most of the major life zones. Forests extend from small alpine meadows on the highest of the San Francisco peaks in northern Arizona through spruce-fir, ponderosa pine, pinion-juniper, oak woodlands to chaparral types. The latter grades into desert scrub, desert grassland and finally to a small area of true desert near the mouth of the Colorado River.

Climate varies widely because of considerable differences in altitude, latitude and the distribution of mountain ranges. Winter rains result from moisture from frontal systems moving in from the Pacific Ocean. Moisture from the Gulf of Mexico is associated with the often violent convective thunderstorms that occur during the summer. Annual average precipitation in the desert areas of the region may be as low as 2.5 inches and greater than 30 inches in some of the higher mountain peaks. Regional average is less than 10 inches per year. Evapotranspiration depletes more than 95 percent of the precipitation before it reaches the streams. There are large variations in temperature across the region. In January, the values range from 20-25°F. in the north to near 55°F. in the south. In July, these same areas record temperatures averaging close to 55°F. and 95°F. respectively.

The present land use is primarily for range, pasture and miscellaneous agriculture (56 percent), with forest and woodland amounting to 27 percent, cropland to 1.5 percent and urban and built-up areas less than 1 percent. By the year 2000, agricultural usage will decline slightly and the urban use will increase. Although the region contains over 36 million acres of land suitable for irrigation, only 1.3 million acres is currently irrigated due largely to a lack of water. Yields per acre of most irrigated crops are among the highest in the nation.

The geology of the Lower Colorado Region includes a broad spectrum of sedimentary, metamorphic and igneous rocks which produce a wide variety of soils. The region lies within two major southwest physiographic provinces, the Basin and Range and the Colorado Plateau. They form a complex of mountains,



·Figure 49. Location and drainage of the Lower Colorado Region

deserts, plains and plateaus, with elevations ranging from 100 feet above sea level near Yuma to 12,611 feet at the summit of Humphrey's Peak north of Flagstaff.

The Basin and Range Province (alluvial Basins region) occupies the southern portion of the region and is characterized by mountain chains and valleys. In the mountain ranges, streams and their tributaries have cut deep gorges, but where buttes and ranges are generally small, valleys consist of a series of partially filled interlocking basins. The basin rims consist of all types of rocks -- sedimentary, granitic, volcanic and metamorphic -- which have generally been subjected to recurrent faulting and tilting. As a result, many ranges consist of masses of rock that are strongly inclined, lying on end, or locally overturned.

The Colorado Plateau Province occupies the northeastern portion of the region and is characterized by cliffs and slopes formed as a result of variations in resistance to erosion. Ledges and cliffs formed of a resistant sandstone and limestone beds are separated by slopes, valleys and badlands carved from weaker intervening strata. In areas adjacent to the Colorado River, canyonlands are extensive, while low mesa-like features predominate in the southern region.

The principal hydrologic feature of the Alluvial Basin region is the alluvial fill of the valleys which provides enormous ground water storage and is capable of large yields to wells, but is recharged at a low rate and primarily from streamflows. A large part of the ground water pumped has come from storage and water levels in the areas of heavy usage have been steadily declining. The Colorado Plateau province has mainly consolidated rock aquifers of low to moderate productivity and recharge. The south edge of the province (Mogollon Rim) is high enough to be the source of a large part of the runoff that recharges the Alluvial Basin area of the region.

In the Colorado Plateau area, one of the principal aquifers is the Coconino Sandstone of Permian age. In other parts of this area, unconsolidated rocks of Cretaceous age serve as aquifers. Recent and Pleistocene alluvial fills are also used for ground water production in some local areas.

In the Alluvial Basins area of the south, the thick, heterogenous mixture of clay, silt, sand and gravel fill the valleys and serve as the principal water source. The transmissivity varies greatly over short distances and with depth in this aquifer. In some areas the primary fill type is clay and little water may be available. In other areas, gravel is predominant and large quantities of water are available to wells. In many instances, the valley fills have been faulted and surface evidence of the faults has been erased by erosion so that locations of the changes in transmissivities are hard to predict prior to drilling. The total depths of most of these aquifers is unknown, although the deterioration of water quality with depth places some limits on production depths.

The estimated volume of ground water, to a depth of 700 feet below land surface, that can be withdrawn from storage under optimum conditions in the Lower Colorado Region, totals 1 billion acre-feet. Although the

amount of ground water in storage in the main alluvial aquifers is large, many problems relative to pumping and use preclude the withdrawal of all the stored water. Land subsidence has occurred in places in Nevada and Arizona where large amounts of ground water have been withdrawn. Although ground water occurs at depths of 200 feet or less below the land surface in about 8,700,000 acres in the region, only about 1,283,000 acres is under irrigated cropland, and many areas that contain easily available ground water are remote from areas of potential use. Some of the available ground water is highly mineralized and would require treatment to be suitable for most uses. Legal constraints and unpredictable economic and technologic factors may affect the practicality of withdrawing deep water or of transporting water long distances to point of use.

In the south central Arizona area, annual ground water levels are presently declining on an average of 8 - 10 feet per year, and are believed to be the principal cause of land subsidence and earth fissures that have occurred in many areas. Although levels will continue to drop, the Central Arizona Project and Southern Nevada Water Project will lessen the rate by 60 percent in 1985 and will provide for the distribution of the region's remaining available water supply to the areas of need.

There are three main sources of water in the region: 1) 2.82 bgd (3.15 maf) of Colorado River water appropriated under the "Law of the River" and originating in the Upper Colorado River Region: 2) local runoff estimated to total about 2.79 bgd (3.12 maf) originating within the region and 3) local ground water resources.

The flow available from the upper basin is dependent upon the resources available and the operating procedures established under the Colorado River Compact (1922) and the Secretary of the Interior. In 1975, inflows from the upper basin averaged 10.0 bgd (11.2 maf). The mean streamflow in the region is estimated to be 1.6 bgd (1.79) maf) with the median being the same. The 5 percent exceedence flow is estimated to be 1.7 bgd (1.90 maf) and the 95 percent value is 1.2 bgd (1.34 maf). The ratio Q_{05}/Q_{95} is 1.4. Although estimates vary somewhat, total water withdrawals in the region in 1975 amounted to 8.9 bgd (9.97 maf) and this value is expected to decline to 7.9 bgd (8.85 maf) by the year 2000. Because of excessive evaporation and transpiration, the total annual usable runoff from the region is estimated to be -0.603 bgd (-0.68 maf). Mined ground water is estimated to be 2.41 bgd (2.70 maf) per year. In 1975, a total of 4.60 bgd (5.15 maf) were consumed, 1.20 bgd (1.34 maf) were lost to evaporation and 4.48 bgd (5.02 maf) were exported from the region. By the year 2000, the annual consumption is estimated to be 4.71 bgd (5.28 maf), evaporation 1.23 bgd (1.38 maf) and exportation 3.93 bgd (4.4 maf). At these levels, the annual average remaining streamflow will be a -1.54 bgd (-1.72 maf) assuming zero ground water mined from storage.

The U.S. Fish and Wildlife Service estimates that a remaining streamflow of 6.86 bgd 7.68 maf) is necessary for optimal fish and wildlife habitat conditions. It is quite obvious, there is not enough water available to the region to satisfy all requirements without extensive ground water mining.

Monthly streamflow distribution within the region is highly variable. In the northern portion (the Colorado Plateau area) runoff has two peaks, one in March and April associated with snowmelt and another in July and August associated with the summer rain storms. Monthly distributions show little to no skewness.

In the central part of the region, maximum runoff occurs in March from snowmelt and is extremely low to near zero in other months of the year. The monthly flow distributions are heavily skewed with the low flows predominant.

In the southern part of the region surface runoff is nearly nonexistent. Flow occurs during the winter months of December, January, and February and during the summer months of July, August and September. The data in all months are highly skewed with the median equal to zero during all months. For the period 1897-1976 and 1930-1976, the runoff series do not show any significant trend.

As of 1975, 90 percent of the water resources withdrawn for use in the region were used for irrigation, about 5 percent was used for domestic purposes. By the year 2000, it is expected that the amount withdrawn for use for consumption will decline to 81 percent and the amount for domestic uses will rise to 8 percent per year.

Surface water storage capacity within the region is large. Normal storage capacity is 19,962 bg (61.2 maf) and flood storage is 23,490 bg (72.1 maf).

Precipitation and temperature records from Flagstaff, Arizona, Grand Canyon, Arizona, and McNary, Arizona were used to evaluate the climatic change scenarios. These stations are located within the present maximum runoff producing areas within the region.

Table 23 shows the estimated ratio of changes in the mean annual runoff for the climatic scenarios, $\overline{Q}$ scenario, as compared to the present, $\overline{Q}$ present, based on analysis of the individual stations. Where the average of all the stations is considered (Table 24) the values are only slightly different with scenarios 3 and 4 being probably significant when specific localities are considered but insignificant when the region is considered.

Should a climatic scenario 1 (warmer and drier) occur, it is estimated that runoff from the region would be reduced to 44 percent of the present. This would obviously cause tremendous legal and economic problems in the region. The total effect, however, would depend on the amount of inflow from the upper basin. Obviously, the water available for agriculture would be greatly reduced if such a climatic change were to occur. Since the amount of surface runoff generated within the region is already so small, the greatest effect on the region would probably relate to an increased demand because of reduced precipitation and increased evapotranspiration. This would lend to even greater ground water mining (as the recharge would also be adversely affected), and result in even faster declining water levels, large increases in cost of pumping and abandonment of agricultural lands.

Scenario	Northwest	Central	East Central	Average
1 (warmer and drier)	.23	.31	.62	.39
2 (cooler and wetter)	1.50	1.41	1.51	1.47
3 (warmer and wetter)	.55	.63	1.04	.74
4 (cooler and drier)	.73	.78	.96	.82

Table 23. Estimated ratios of $\overline{Q}$ scenario/$\overline{Q}$ present for climatic change scenarios based on individual station records within the Lower Colorado River Region.

Scenario	Ratio $\overline{Q}$ scenario/$\overline{Q}$ present
1 (warmer and drier)	.44
2 (cooler and wetter)	1.69
3 (warmer and wetter)	.98
4 (cooler and drier)	.98

Table 24. Estimated ratios of $\overline{Q}$ scenario/$\overline{Q}$ present for regionally averaged climatic data within the Lower Colorado Region.

An occurrence of a climatic change as described by scenario 2 would have a tremendous beneficial result in that the surface runoff would be increased by nearly 1.7 times. The average annual runoff would increase from 3.2 bgd (3.6 maf) to near 5.4 bgd (6.0 maf) and with accompanied increased recharge would probably reduce or eliminate the need for ground water mining. Some additional flood protection would be necessary but the present large reservoir storage capacity would prove to be very beneficial.

The speculative impacts on various aspects of the hydrologic and water resources systems by the occurrence of climatic change scenarios 1 and 2 are shown in Tables 29 and 30 in the Appendix.

REGION 16 - GREAT BASIN REGION

The Great Basin Region includes an area 139,000 square miles; 67 percent is in the state of Nevada, 32 percent in Utah and 1 percent in Idaho (Figure 50). Physiographically, the region consists of desert valleys separated by north-south trending mountain ranges.

The climate of the Great Basin varies greatly because of differences in elevation, range in latitude and irregular distribution of mountain ranges. Precipitation ranges from 3 inches per year in the lower elevations to 16 inches in the northern valleys and 60 inches in the high mountains. Most precipitation comes in the winter. Average annual temperature ranges from about 60°F. in the south of the region to 30°F. in the high mountain valleys.

Land uses in the Great Basin are varied. The majority of land, 72 percent, is used for agriculture, of which 3 percent is irrigated cropland and the rest grazing land. About 14 percent is forest (mixed conifers) and less than 1 percent is urban. Mining, military and other uses account for about 13 percent. Little change is anticipated by the year 2000.

The geology of the area consists of rocks of nearly all ages from Precambrian to recent with the older rocks, generally igneous and metamorphic, forming the mountain ranges and the younger rock (alluvium) occupying the valleys. Water occurs in the valley alluvium, carbonate sedimentary rocks, and in volcanic rocks. Although the total distribution of the aquifers is unknown, water is principally pumped from the valley alluvium throughout the region. Known volcanic aquifers occur in a small area in south central Utah. The carbonate rocks in most areas are highly permeable and transmit substantial quantities of water to large springs in eastern Nevada and western Utah.

A large amount of ground water is stored in the consolidated rocks that occur both in the mountains and beneath the valley alluvium. These ground water reservoirs are not generally continuous and are extremely difficult to evaluate. Local barriers formed by faults or rock units of low permeability produce a complex pattern of perched ground water bodies in the mountains.

Ground water is an important resource of this region. It is used to supplement low flow of perennial streams and as a primary water source for many towns in the central part of the region. Currently, there is relatively little overdraft of ground water.

Estimates of total stored water are large, 945×10^{12} gallons (2900 maf) but the amount that can practically be withdrawn from any given area is limited by quality, distribution and allocation. The amount that can be feasibly withdrawn is estimated to be 524 maf. In most places there is a progressive increase in dissolved sollids with increasing depth. In areas of natural discharge in the vicinity of terminal lakes and sinks, the

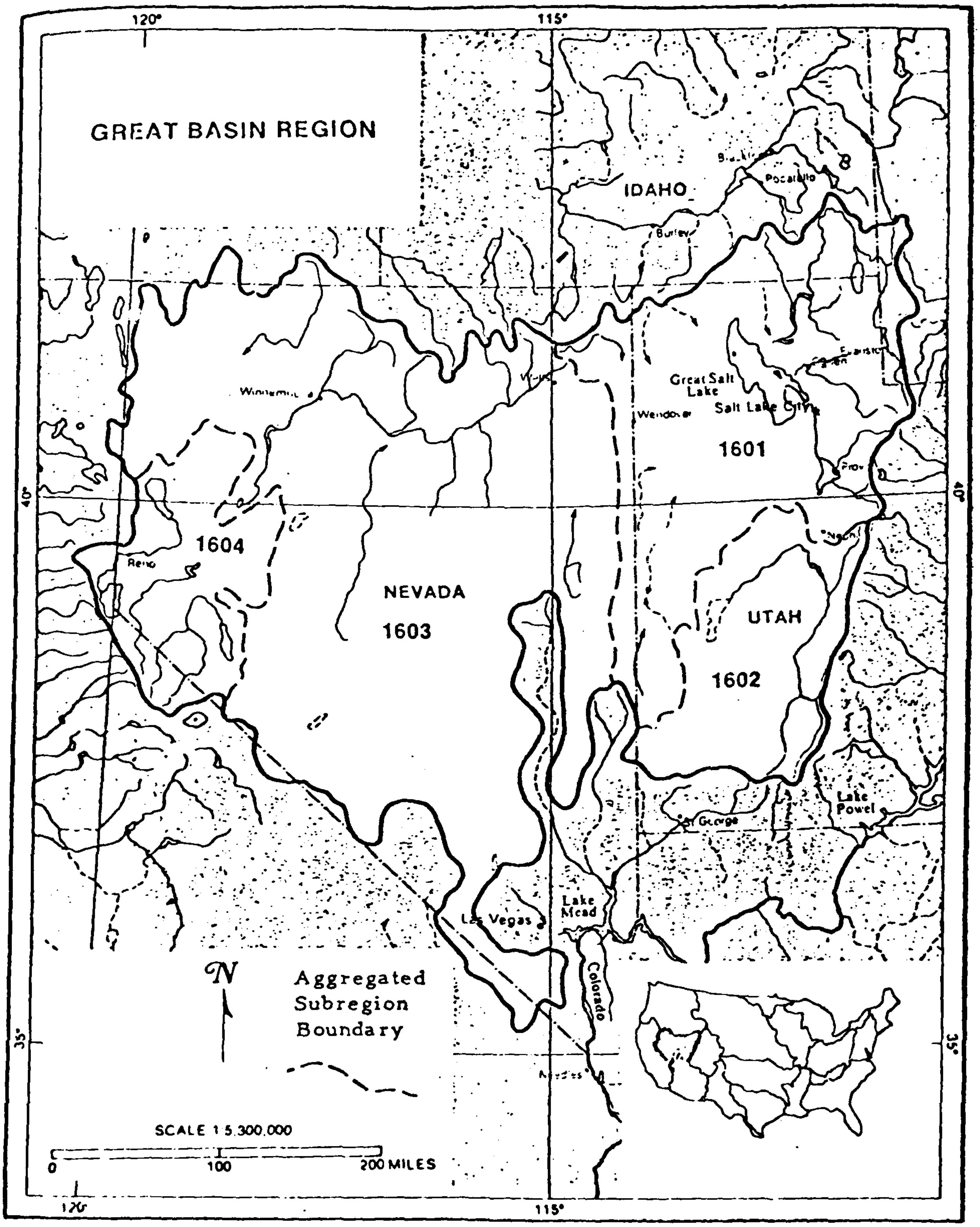


Figure 50. Location and drainage of the Great Basin Region

ground water is commonly saline to briny. Present ground water withdrawals amount to 1.4 bgd (1.57 maf) with 0.6 bgd (0.67 maf) being in excess of recharge.

Streamflow is closely tied to precipitation and elevation. All of the streams in the region terminate in closed basins some of which contain permanent lakes, for example Pyramid and Walker Lakes in Nevada and the Great Salt Lake in Utah. Minor streams range from perennial to intermittent. Some are tributary to permanent rivers while other flow only after major storms. Mean annual streamflow generated within the region is estimated to be 10.5 bgd (11.8 maf). The median is 9.8 bgd (11.0 maf) indicating a slight predominance of below average streamflow. The 5 percentage exceedence flow is 19.0 bgd (21.3 maf) and the 95 percent exceedence flow is 4.6 bgd (5.2 maf). Q_{05}/Q_{95} is 4.1. The estimated mean annual runoff generated in the region is 13.95 bgd (15.6 maf). Imports amount to 0.10 bgd (0.11 maf) but are expected to increase tp 0.23 bgd (0.26 maf) by the year 2000. Ground water is currently being mined at a rate of 0.59 bgd (0.66 maf).

Present total fresh water withdrawals are 7.99 bgd (8.95 maf) of which 3.78 bgd (4.23 maf) are consumed within the region. By the year 2000 the total withdrawals are expected to decline some to 7.26 bgd (8.13 maf) but the consumption will rise to 4.03 bgd (4.51 maf).

Currently, 87 percent of the water withdrawn is used for irrigation and 4 percent for domestic purposes; miscellaneous uses account for the remainder. By the year 2000, irrigation use is expected to fall to 80 percent and domestic use will rise to 7 percent. Evaporation losses are estimated to average 0.33 bgd (0.37 maf) per year. The U.S. Fish and Wildlife Service estimates that 8.18 bgd (9.16 maf) of streamflow is necessary for optimal fish and wildlife habitat conditions.

Monthly distribution of runoff varies over the region. In the northeast part, peak runoff months are April and May and lowest flow occurs during July and August; the data are only slightly skewed toward the low flows. In the southeast, highest flow occurs during May-July with low flow during September-March. The data are not skewed to any appreciable degree. In the central part, high flows occur during April-July and low flow during the remainder of the year. The data are moderately skewed with low flows predominant. In the western part, high flows occur during April-June, low flow August-September and moderate flow during December-March. The individual monthly data are moderately skewed with low flow predominating.

Unregulated streams commonly discharge 60 to 80 percent of their annual flow in a 3 month period starting in April or May. Maximum yearly flows have been as much as 25 times the minimum flows and average flows for a maximum month have been 100 times the flow of a minimum month.

The reservoir storage capacity is not great; normal storage is 1,240 bg (3.77 maf) and the flood storage capacity is 1,368 bg (4.15 maf).

In evaluating the climatic change scenarios, climatic data from Reno, Nevada, Logan, Utah, and Lehman's Cave National Monument, Nevada were used

to represent the region.

The estimated ratios of $\overline{Q}$ scenario for each of the climatic change scenarios to $\overline{Q}$ present are shown in Table 25. The results of the same analysis except based on the regional averages of temperature and precipitation are shown in Table 26.

Scenario	West	Northeast	Southeast	Average
1 (warmer and drier)	.63	.60	.20	.48
2 (cooler and wetter)	1.75	1.64	2.50	1.96
3 (warmer and wetter)	1.13	1.00	1.00	1.04
4 (cooler and drier)	1.13	1.00	1.50	1.21

Table 25. Estimated ratios of $\overline{Q}$ scenario/$\overline{Q}$ present for mean annual flows based on individual climatic stations within the Great Basin Region.

Scenario	Ratios $\overline{Q}$ scenario/$\overline{Q}$ present
1 (warmer and drier)	.55
2 (cooler and drier)	1.82
3 (warmer and wetter)	1.14
4 (cooler and drier)	.95

Table 26. Estimated ratios of $\overline{Q}$ scenario/$\overline{Q}$ present for average temperature an precipitation within the Great Basin Region.

A scenario 1 (warmer and drier) change would reduce the regional mean annual runoff to an estimated 55 percent. This would reduce the mean annual runoff to about 7.7 bgd (8.6 maf) which is just about equal to the current fresh water withdrawal rate. Since current regional water demand is not excessive as to supply, with a larger conjunctive use of the large ground water reserves, the region could cope with such a change reasonably well.

A climatic change similar to that of scenario 2 (cooler and wetter) would increase the mean annual runoff by about 1.8 times. The mean regional runoff would increase from 13.95 bgd (15.62 maf) to 25 bgd (28 maf). Although flooding would be more of a problem than at the present and many of the old closed basin lakes would appear again, if the present land use continues, the region could cope with this type of a change with reasonable ease.

Scenarios 3 and 4 are considered to be regionally insignificant although locally within the region they would be significant. Tables 31 and 32 in the Appendix show the speculative impact matrices for scenario 1 and 2 climatic changes.

REGION 17 - PACIFIC NORTHWEST REGION

The Pacific Northwest Region (Figure 51) consists of 270,885 square miles and includes all of the Columbia River Basin in the United States; the river basins in Washington and Oregon that drain directly into the ocean; and that part of the Great Basin located in Oregon. The region includes major parts of Oregon, Washington and Idaho and minor portions of Wyoming, Utah and Nevada.

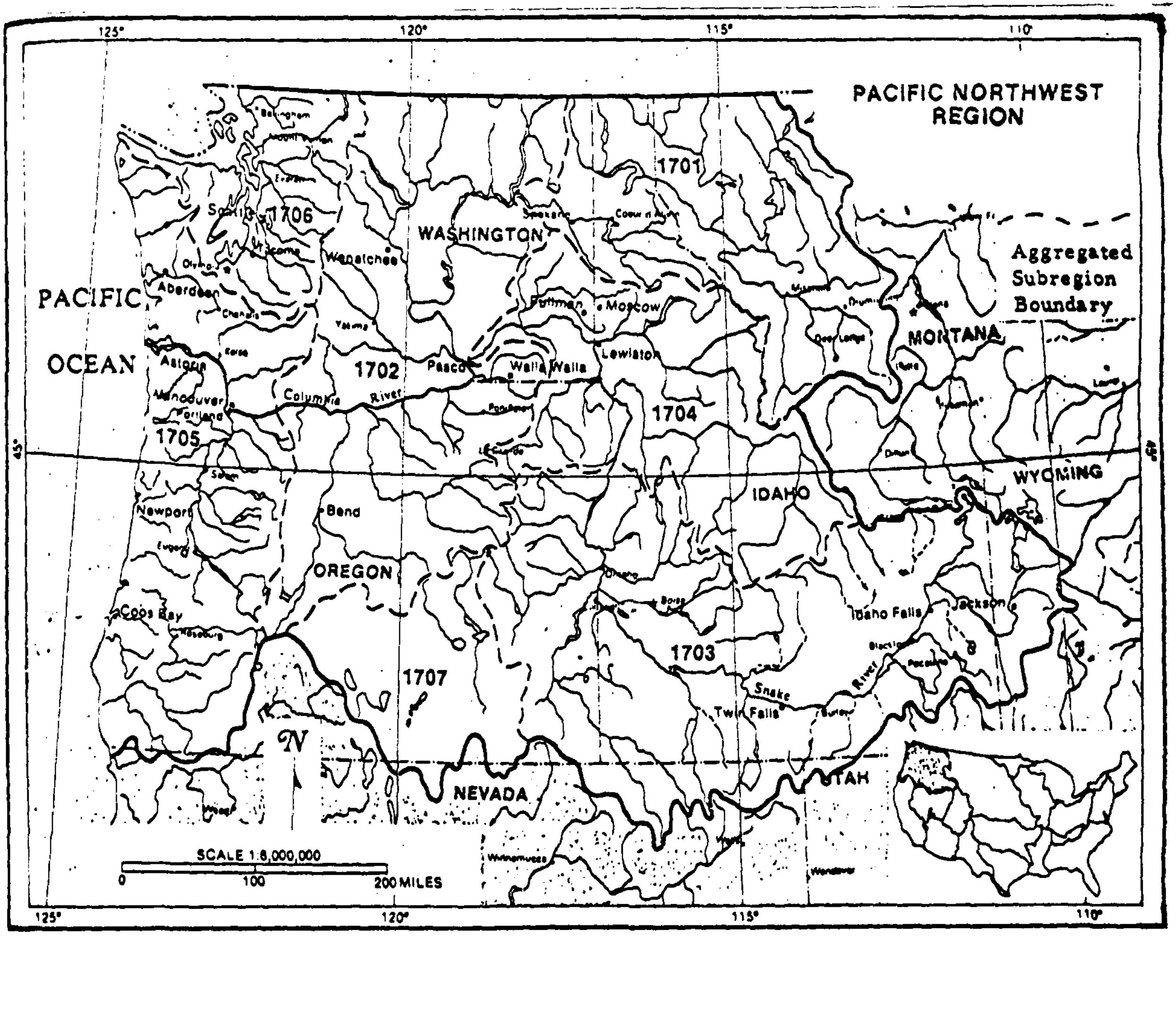


Figure 51. Location and drainage of the Pacific Northwest Region.

From west to east, the Coast Range, Willamette Valley-Puget Sound Trough, and Cascade Range transect Washington and Oregon in a north-south trend. The Coast Range is relatively low (2,000 to 4,000 feet in elevation). The tallest are the Olympic Mountains, 4,000 to 8,000 feet in elevation, located at the north end of the Coast Ranges. Streams draining these mountains are short with steep gradients. The Willamette Valley-Puget Sound Trough is low (generally 1,000 feet in elevation). The Cascade Range is substantially higher than the Coast Range ranging in elevation from 9,000 to 13,000 feet above sea level.

The Columbia River Plateau, a basalt flow dissected by steep-walled stream valleys lies immediately east of the Cascade Range. Southeast of the Columbia River Plateau, the Blue Mountains extend from southwestern Washington to central Oregon. Peaks range from 7,000 to 10,000 feet in elevation. A closed basin occupies south central-southeastern Oregon. The Snake River Plateau lies in southern Idaho and western Wyoming. The northern Rocky Mountains form the eastern boundary of the region and are composed of north-south ranges with long, narrow valleys containing the area's principal streams. Elevation ranges from 2,000 to 12,000 feet above sea level.

The heaviest annual precipitation in conterminous United States occurs on the western slopes of the Coast and Cascade Ranges, exceeding 200 inches in the Olympic Mountains. From the crest of the Coast Range, annual precipitation decreases to about 35 inches in the Willamette Valley-Puget Sound Trough and then increases to 100 inches or more along the crest of the Cascades. About two-thirds ofthe annual precipitation occurs from October to March. East of the Cascade Range in central Oregon and Washington, precipitation decreases rapidly to 10 inches or less in the valleys and plateaus. Mountain areas have a total of 40 to 50 inches. The Snake River Plateau receives from 6 to 15 inches of annual precipitation, with 40 or more inches occurring in the mountains along the southern edge. In the northern Rocky Mountains, annual precipitation ranges from 10 to over 70 inches. At the higher elevations, much of the precipitation occurs in the form of snow. Maximum snowpacks, occasionally to depths of 20 to 30 feet, are generally found at elevations above 5,000 feet. Heavy snowpacks on many of the highest mountains have formed glaciers. West of the Cascade Range, winters are milder and summer days cooler than at locations of similar elevation east of the mountains. January temperatures average 36°F. in low-lying areas west of the Cascades as compared to 32°F. in the warmest valley areas to the east. The corresponding July temperatures are 62°F. and 76°F.

At the present, about 49 percent of the region is in forest and woodland, 31 percent is used for pasture and rangeland, cropland occupies about 11 percent and urban areas less than 1 percent. These values are not expected to change appreciably by the year 2,000.

Navigation is important in the region. The Columbia River serves as a major waterway to Bonneville dam and up the Snake River to Lewiston, Idaho.

Federal reserved lands and Indian reservations occupy a major portion

of the region's land area. Of the water originating on those lands or passing through or by them, the Federal Government and Indian tribes claim (under the Reservation Doctrine) the right to use such amounts as may be deemed necessary to fulfill the purposes for which the lands were reserved. Until these claims are quantified, the legal status of all water originating on or passing through or by them is in doubt. Since most of the water in the region originates on Federal lands, its continued availability for use outside reserved lands is in doubt.

The predominant rock types in the region are of volcanic origin. More than half of the region is underlain by lava flows, pyroclastics or sedimentary rocks composed of volcanic materials. Other rock types include granitic, metamorphic, and consolidated sedimentary rocks.

The Coast Range consists principally of sandstones and shales together with basaltic volcanic rocks and related intrusives. Ground water yields are best in dune and beach sands along the coast and in certain alluvial deposits.

Alluvial, lacustrine, glaciofluvial and glacial deposits underlie the floor of the Willamette Valley-Puget Sound Trough, located between the Coast and Cascade Ranges. Wells drilled into these deposits have moderately large to very large yields.

The Cascade Range consists of a rugged group of mountains of folded, faulted and uplifted older igneous and metamorphic rocks and some younger volcanic rocks which have remained relatively unaltered. The younger rocks are porous and highly permeable, and streams draining such areas are characterized by high base flows.

The Columbia Plateau consists of volcanic rocks overlaid by varying thicknesses of loess, glacial outwash, lacustrine silts and other materials. The loess soils are deep and fertile but are easily eroded. Many of the formations are highly porous and store large volumes of water when saturated. Much of the area is, however, semi-arid and little water is available for recharging aquifers.

The Blue Mountains, including the Wallowa Mountains consist of a core of older crystalline, volcanic, and consolidated sedimentary rocks surrounded by younger lavas and pyroclastic rocks. The younger rocks are generally higher in porosity and permeability than the older. The Oregon Closed Basin comprises a high lava plateau with numerous basins and ranges formed by block faulting. Most of the rocks are moderately to highly porous and permeable.

The Snake River Plateau is an extensive volcanic plateau containing both older and younger rocks. In some areas, the basalt surface is virtually unweathered and little residual soil has developed. The younger basalts are moderately to highly porous and permeable. The area is, however, semi-arid and receives most of its water from surface runoff and ground water inflow from basins flanking the plateau.

The northern Rocky Mountains, occupying the northeastern portion of the region, consist of sedimentary rocks and metamorphic rocks. Alluvial and outwash deposits in the valleys store and yield large amounts of ground water.

Ground water is an essential element of the water resources of the region. Not only are large quantities of water for a variety of uses obtained from wells and springs, but also a large part of the surface water supply is maintained by discharge from aquifers, especially during periods of dry weather when the flow of many streams is composed mostly or entirely of effluent ground water.

Only in coastal areas does any significant quantity of ground water (excluding evapotranspiration) leave the region that does not appear as a component of stream discharge. In all other areas utilization of ground water does not add to the total available supply because of relatively small storage and close hydraulic connection with surface supplies. It does offer opportunities for management by augmenting minimum streamflows and increasing firm supplies by drawing water from underground storage during dry periods and replacing the ground water by natural or arificial recharge during periods of excess runoff.

Ground water can be obtained at most places in the region (Figure 52) although the quantities obtainable from wells range from a few to many thousand gallons per minute. Also, the depth that wells must be drilled to obtain adequate water ranges from a few feet to more than a thousand feet. The great differences are related chiefly to differences in geology, the quantity of precipitation, topography, and drainage.

About 42 percent of the region is underlain by aquifers with low porosity and permeability that will generally yield only small supplies of ground water. These units are, however, confined mainly to thinly populated areas where water needs are comparatively small and surface water supplies are plentiful.

West of the Cascade Range the major aquifers are chiefly sand and gravel in the alluvial and glacial deposits. Many wells with yield capacites ranging from 20 to 2,000 gallons per minute have been drilled in these deposits in ASR 1706 and in the Willamette, Cowlitz, Chehalis, and other river valleys.

In the plateaus of central and eastern Washington, north-central and northeastern Oregon, and west-central Idaho, basalt of the Columbian River Groupd and similar basalt is the most widespread major aquifer and yields up to 2,000 gallons per minute to wells. Recharge from direct precipitation is generally small, but some areas receive additional recharge from streams draining adjacent mountain areas or from irrigation seepage. Over large areas of the plateau, however, recharges are entirely from the scanty local rainfall which limits the quantity of ground water that can be obtained.

Alluvial deposits are important aquifers along the Columbia River downstream from Grand Coulee Dam; in the Spokane, Ikanogan, Yakima, and Walla

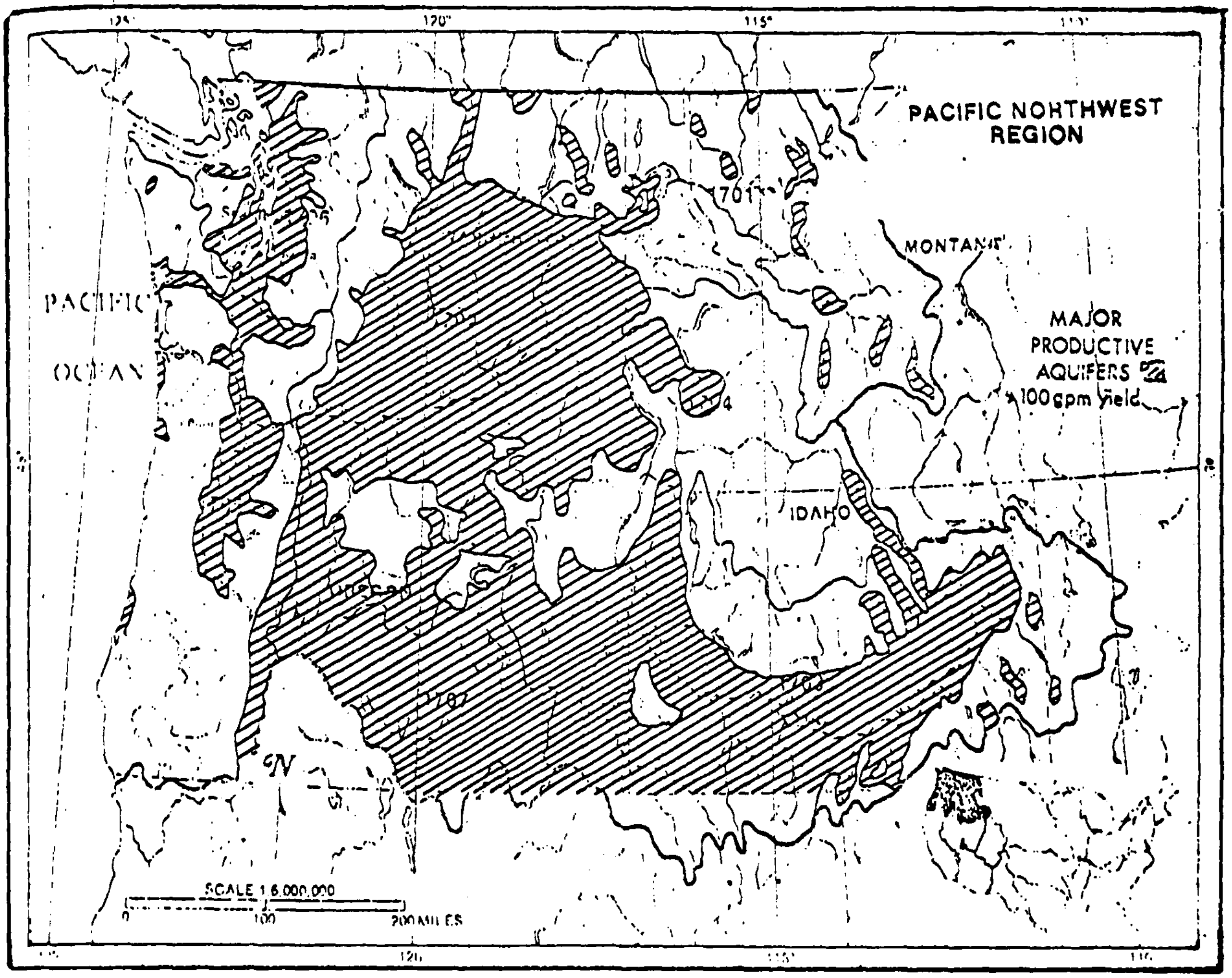


Figure 52. Distribution of major aquifers in the Pacific Northwest Region.

Walla River valleys; and in the Ephrata-Moses Lake and Pasco areas. Alluvial deposits are also major aquifers in valleys in northern Idaho and Montana and in such places as the Rathdrum Prairie, and the Bitterroot, Flathead, Kootenai, and similar valleys, Volcanic rocks, sedimentary strata, and valley alluvial deposits are important aquifers in south-central and southeastern Oregon and in southwestern Idaho but have been developed only at a few places. Extensive aquifers underlie the Snake River and more ground water is withdrawn in that area than in any other part of the region. Basalt is the major aquifer in the eastern Snake River Plain, but alluvial deposits are important near the Snake River and in tributary valleys.

Total ground water production in the region is estimated to be 7.4 bgd (8.31 maf) of which 0.6 bgd (0.7 maf) is mined. The total amount in storage that can be feasibly withdrawn is estimated to be 180.0 x 10^{12} gallons (552 maf).

Current mean annual streamflow measured at the outflow point of the region is 255.3 bgd (285.9 maf). The median is nearly the same indicating little skewness in the distribution between high and low flows. The 5 percent exceedence value is 344.7 bgd (386 maf) and the 95 percent exceedence flow is 179.7 bgd (201.3 maf). Q_{05}/Q_{95} is 1.7. The annual runoff is estimated to be 268.5 bgd (300.7 maf). Water imported into the region is negligible and that mined from local aquifers is about 0.6 bgd (0.7 maf) per year.

Presently, total withdrawals are 37.5 bgd (42.0 maf) per annum with consumption amounting to 11.1 bgd (12.4 maf). The total withdrawals are expected to decline to 33.8 bgd (37.9 maf) per year by the year 2000 but the consumption is expected to rise to 15.2 bgd (17.0 maf). Irrigation is expected to remain the greatest user of water in the region with 88 percent used now and 89 percent predicted by the year 2000. Manufacturing currently uses 6 percent but this is expected to decline to 3 percent. Domestic use is only 2 percent and may rise to 3 percent. Other usages are small, generally less than 1 percent per category such as steam-electric, mineral processing and the like. Normal surface water storage is relatively large at 17,839 bg (54.7 maf) with flood storage adding an additional 21,257 bg (65.2 maf). Evaporation losses are estimated to be 2.01 bgd (2.25 maf). Streamflow necessary for optimal fish and wildlife habitat is estimated to be 241.0 bgd (269.9 maf).

Monthly streamflow distribution to the east of the Cascade Mountains is different from that west of the Cascades. In the eastern part, maximum streamflow normally occurs during April, May and June although in some areas February and March can also be high flow months. This variability may be more than 3 times as great in one locality as in another. To the west of the Cascades, high flows occur during the period November-June with August, September and October being the only low flow months. The distributions of high and low flows within the individual months show only slight skewness.

Only one area shows a significant trend in the annual series, the area immediately east of the Cascades. The trend is a positive 0.091 percent per year for the period 1909-1977. The cause may be climatic but more probably is related to land use practices.

Precipitation and temperature statistics used to asses the climatic change scenarios include Boise, Idaho, Missoula, Montana, Spokane, Washington and Portland, Oregon. The ratios of the estimated mean annual runoff for the climatic change scenario to that of the present is shown in Table 27. The station data are also averaged and the ratios estimated. The results are shown in Table 28.

Scenario	West	North-Central	South-Central	East	Ave.
1 (warmer and drier)	.73	.63	.11	.63	.53
2 (cooler and wetter)	1.46	1.50	1.67	1.50	1.53
3 (warmer and wetter)	1.09	1.00	.83	1.00	.98
4 (cooler and drier)	.91	1.00	.83	.88	.91

Table 27. Estimated ratios of $\overline{Q}$ scenario/$\overline{Q}$ present for mean annual flows for each climatic change scenario based on individual station data within the Pacific Northwest Region.

Scenario	Ratio $\overline{Q}$ scenario/$\overline{Q}$ present
1 (warmer and drier)	.64
2 (cooler and wetter)	1.44
3 (warmer and wetter)	1.04
4 (cooler and drier)	.83

Table 28. Estimated ratios of $\overline{Q}$ scenario/$\overline{Q}$ present for averaged climatic data within the Pacific Northwest Region.

A climatic change in this region similar to that described by scenario 1 (warmer and drier) would result in an average runoff reduction of 36 percent. Various subregions could have greater or lesser reduction as is shown in Table 27. The result would be an estimated average annual runoff of about 172 bgd (192 maf). This amount is well above total withdrawals (37.5 bgd) but is considerably less than the 241 bdg (270 maf) considered necessary for optimal fish and wildlife habitat.

It is conjectured that the duration of low flows would be longer because of reduced baseflow related to a decline in ground water levels. Navigation and hydroelectric power generation would be adversely affected. The hydroelectric system, which furnishes most of the region's electric energy, is particularly vulnerable to periods of low flow. This was demonstrated during the 1976-1977 drought when near-critical conditions were reached.

A climatic change such as scenario 2 (cooler and wetter) would result

in an increase of 1.4 times the present mean annual flow. The mean annual total runoff would be increased to 386 bgd (433 maf). Obviously in a region already water-rich, this increase could cause considerable flooding of low areas, inward movement of the estuaries and drainage problems in general. Reservoir storage would be inadequate for flood control but reliability of the system would be good. In addition to increased reservoir capacity some drainage of low lands along the coast might be necessary.

The impacts of scenarios 3 and 4 are considered to be insignificant on a region wide basis.

A more detailed analysis of the speculative impact analysis of changes of the types described by scenarios 1 and 2 are included in Tables 33 and 34 in the Appendix.

REGION 18 - CALIFORNIA REGION

The boundaries of this region are essentially those of the state of California except that it also includes Klamath County, Oregon (Figure 53). This elongated region includes 164,839 square miles and stretches for 780 miles in a north-south direction. Width varies from 150 to 350 miles. It is a region of contrasts with 1,050 miles of coastline and contains both the highest (Mt. Shasta, 14,161 feet) and the lowest (Death Valley, -282 feet) areas in the conterminous United States. These contrasting features have produced places of great beauty, spectacular landscapes and unique habitats. Numerous National Parks, Forest and Monuments, along with historical and archaelogical sites are located in the region.

The natural vegetation reflects the differences in climate and physiography. Vegetation types vary from the almost-barren deserts through chaparral grasslands, coniferous forests and culminating in the giant Sequoias located in the fog belt along the upper-central coastline.

The overall climate of the region is mild with two seasons, wet winters and dry summers, in contrast to the usual four seasons characteristic of most temperate climates. The coastal areas have a marine climate with warm winters and cool summers and small day-to-day and seasonal changes. The climate becomes continental towards the interior as the influence of maritime air becomes progressively less. The interior experiences considerably greater ranges in daily and seasonal temperatures than occur along the coast. Based on long-term records, Death Valley is one of the hottest places on the earth. Precipitation also varies widely, ranging from an average of 50 inches in the mountains to less than 10 inches in the deserts.

Land use in the region is distributed as follows: pasture, range and other agriculture, 28 percent; irrigated cropland, 8 percent; other cropland, 2 percent; forests and woodlands, 41 percent; urban and built up areas, 3 percent; water, 2 percent; and other, 16 percent. Much of the non-agricultural land is used for more than one purpose. Grazing, for instance, is combined with timber production, wildlife habitat, recreation, watershed, etc. Favorable climate, fertile soils and the availability of water for irrigation have made California the nation's number one state in agriculture in terms of cash value.

The general geology of the region determines the extent and availability of ground water resources. The Coast Range, composed primarily of sedimentary rocks, runs parallel to the coast line from Oregon to lower California. A vast valley, the Central Valley, lies to the east of these mountains and contains sediments several miles in thickness. The high Sierra Nevada Mountains on the east side of the Central Valley, are composed of igneous rocks and are generally non-water bearing. In the southeastern corner, the Basin and Range igneous-metamorphic mountain ranges are the predominant feature.

Most of the ground water in the California region is contained in the valley and plains that receive runoff from the mountains. The Central Valley

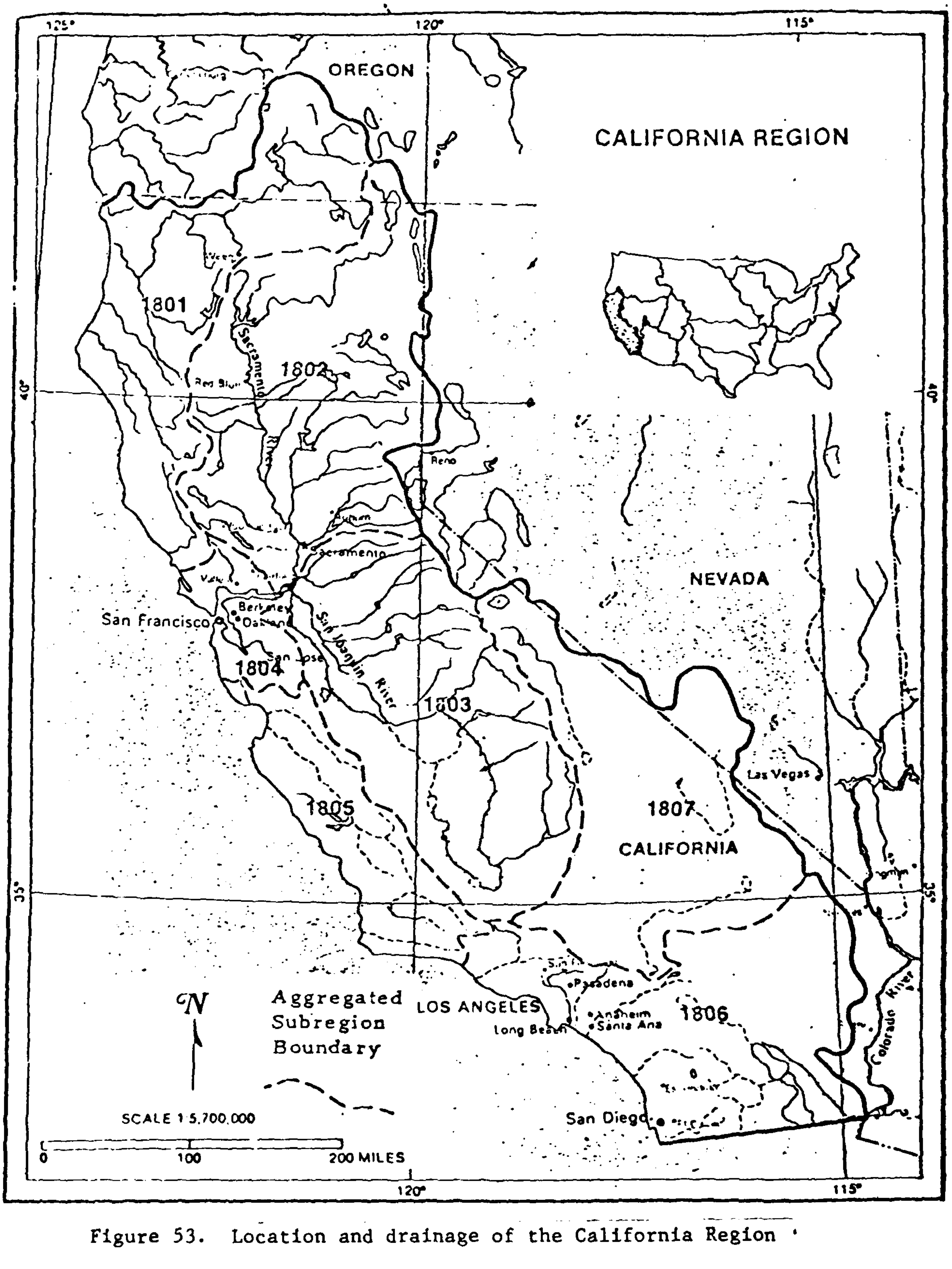


Figure 53. Location and drainage of the California Region

is a classic example of this situation. Here the ground water reservoir includes numerous sand and gravel aquifers formed by stream-carried sediments from the mountains and separated by interstratum sediments of silt and clay. There are also deep confined aquifers that are separated from the shallow aquifers by extensive beds of clay. Fresh water is present from depths of 400 to 4,000 feet below mean sea level.

Most of the ground water in the Coast Range area occurs in the intervening valleys and coastal plains and are recharged by streams. East of the Sierra Nevada mountain range, ground water reservoirs were formed under the valleys and plains with recharge coming from intensive storm runoff.

In the northeastern part of the region, the Modoc Plateau consists of a thick accumulation of lava flows, tuffs and small volcanic cones. Many of these rocks are excellent aquifers, readily recharged by precipitation and permeable enough to provide large quantities of water. The regional distribution of the major aquifers is shown by Figure 54.

Total ground water withdrawal in the region is 19.2 bgd (21.5 maf) and 2.2 bgd (2.5 maf) is in excess of recharge. The amount of ground water that can feasibly be withdrawn is estimated at 251 maf. At current rates of withdrawal it is estimated that one-half of the water in storage will be depleted in about 50 years.

Water use in the California Region is the most extensive of all regions. The average annual runoff is estimated at 68.9 bgd (77.2 maf); 4.49 bgd (5.03 maf) is imported from the Colorado River system and water mined from ground water sources averages 2.20 bgd (2.5 maf). Present withdrawals average 39.64 bgd (44.4 maf) of which 26.64 bgd (29.8 maf) are consumed. Irrigation accounts for about 87 percent of the present withdrawals. Annual evaporation losses account for 0.67 bgd (0.75 maf). The remaining streamflow averages 48.25 bgd (54.0 maf) with an estimated 33.13 bgd (37.1 maf) needed for optimal fish and wildlife habitat.

The average annual streamflow generated within the region is slightly skewed with low flows predominant; the median is 45.2 bgd (50.6 maf), slightly less than the mean. The 5 percent exceedence flow is 88.7 bgd (99.3 maf) and the 95 percent exceedence flow is 20.0 bgd (22.4 maf). Q_{05}/Q_{95} is 4.0.

In the northern part of the region, and in a narrow band along the coast south of San Francisco, the peak flows generally occur in December, January and February. Flow then decreases in a typical baseflow fashion to the June-October period when little to no flow occurs. The monthly distributions are moderately skewed with low flows predominating in all months. In the eastern part of the central and southern parts of the region, runoff is largely from snowmelt with high flows during April, May and June. Low flows occur during July-November and moderate flows from December-March. The monthly flow distributions are only slightly skewed with low flows predominant.

The runoff series from the mountainous eastern edge of the region

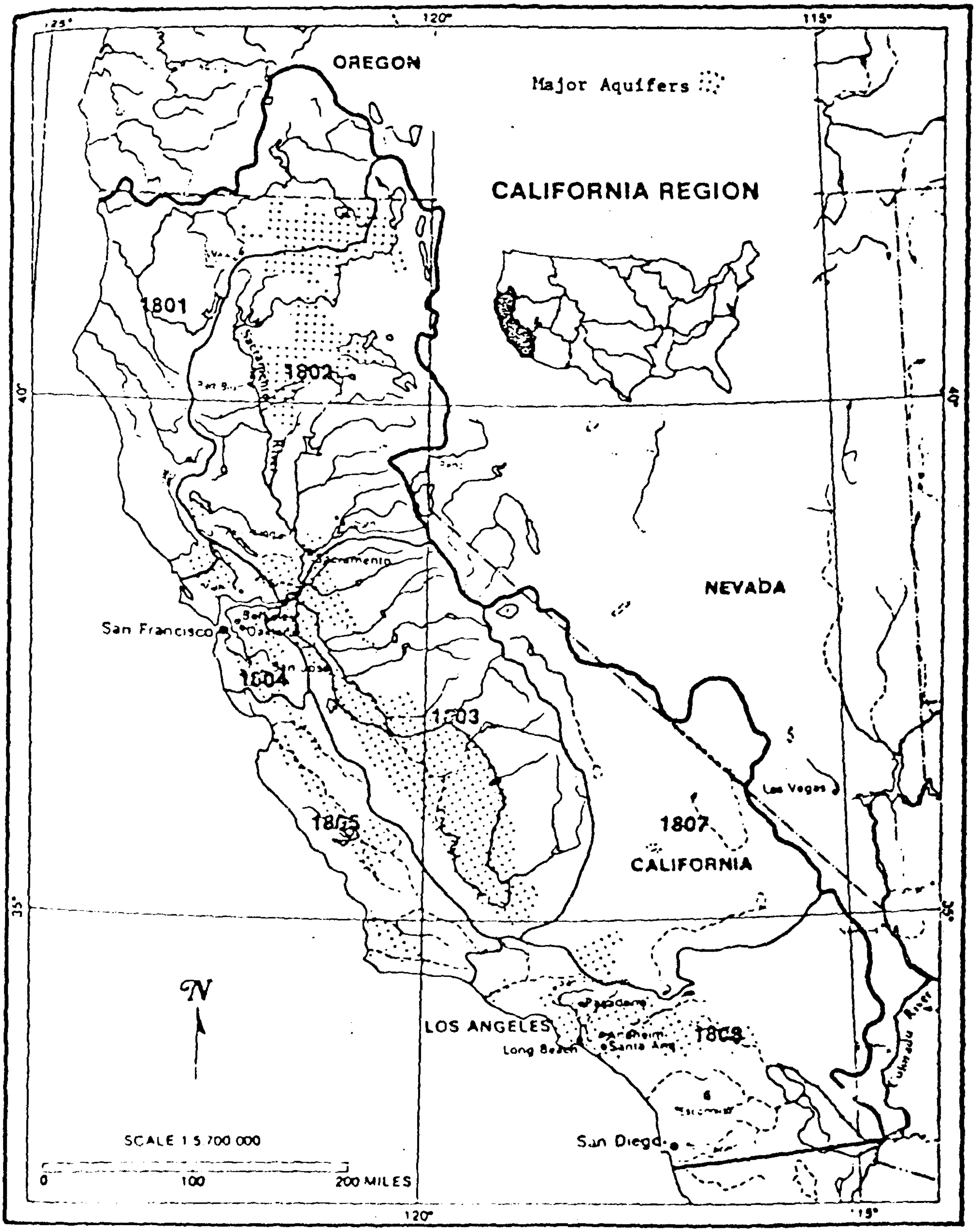


Figure 54. Distribution of major aquifers in the California Region.

shows a significant trend of -0.576 percent per year over the period 1907-1977. The other areas do not show significant trends although the existing records are for a shorter period, 1925-1977.

In general about 60 percent of the region's water supply is derived from regulation and diversion of the natural runoff from surface streams. The other 40 percent comes from ground water sources; about 50 percent of the irrigation demand is from ground water.

Climatic data from San Francisco, Sacremento, Fresno, Lake Arrowhead and Los Angeles were used to reconstruct the various climatic scenarios. The results are shown in Tables 29 and 30.

Scenario	San Francisco	Sacremento	Fresno	Lake Arrowhead	Los Angeles	Ave.
1 (warmer and drier)	.52	.53	.50	.71	.10	.47
2 (cooler and wetter)	1.80	1.87	2.00	1.51	1.70	1.78
3 (warmer and wetter)	1.00	1.20	1.25	1.16	.80	1.08
4 (cooler and drier)	1.00	1.00	1.05	.94	.70	.94

Table 29. Estimated ratios of $\overline{Q}$ scenario/$\overline{Q}$ present for mean annual runoff in the California Region.

Scenario	Ratio $\overline{Q}$ scenario/$\overline{Q}$ present
1 (warmer and drier)	.56
2 (cooler and wetter)	1.63
3 (warmer and wetter)	1.07
4 (cooler and drier)	.93

Table 30. Estimated ratios of mean annual runoff for climatic change scenarios to present runoff for regionally averaged data in the California Region.

A scenario 1 (warmer and drier) climatic change would likely reduce the mean annual runoff by about 50 percent of the present, with variations

between 10 and 70 percent in different localities. The 50 percent reduction would produce 34.5 bgd (38.6 maf) which is substantially less than current withdrawals at 39.6 bgd (44.3 maf). Firm yields from existing reservoirs would decline as inflows become more variable, less persistent and smaller in magnitude. Ground water recharge would be substantially reduced but withdrawals would increase. Since the present use of ground water is near maximum, use of this source to make up the deficit is not a viable alternative. Irrigated agriculture would likely have to be drastically curtailed, causing serious economic and social repercussions. The decreased water supply for irrigation, coupled with increased evapotranspiration, would aggravate an already serious salinity problem in the highly productive central valley.

A scenario 2 (cooler and wetter) change would increase the present annual runoff by 1.65 times (to 113.7 bgd; 127.3 maf). In general this type of change would be beneficial, especially so in providing more water for irrigated agriculture. Some additional flood protection would be necessary and drainage problems would increase in some areas.

Climatic changes induced by scenarios 3 and 4 would be trivial in the region. Speculative climatic impacts induced by scenarios 1 and 2 are shown in Appendix Tables 35 and 36.

Discussion of Climatic Impacts

The preceding region-by-region evaluation of climatic change impacts has shown that a change as described by scenario 1 (warmer and drier) would have the greatest adverse effect nationally. Most of this would be in the regions located west of the Mississippi River. A climatic change as described by scenario 2 (cooler and wetter) would have mostly beneficial effects, again with the greatest impact being in those regions west of the Mississippi River where the present water supply is already nearly allocated. Scenarios 3 (warmer and wetter) and 4 (cooler and drier) are trivial in most regions. Only in the Upper Colorado Region did scenario 3 prove to be non-trivial on a region-wide basis. There were some areas within regions, especially in the west, where this did not appear to be true. Time limitiations, however, did not permit analysis below the regional level.

The present annual runoff and that predicted for scenario 1 and 2 conditions is shown graphically on Figure 55 for each of the 18 regions. In each case the center bar represents present conditions while the scenario 1 and 2 projections are shown by the upper and lower bars respectively.

The extremes are well defined by such water-rich regions as the Pacific Northwest and the South Atlantic-Gulf and the contrasting, water-poor Rio Grande and Lower Colorado Regions. It is ironical that none of the regions adjacent to the South Atlantic-Gulf Region are water-poor, while the opposite is true for the Pacific Northwest. Even under scenario 1 conditions, total runoff from the Pacific Northwest is greater than the present runoff from the California, Great Basin, Lower Colorado and Upper Colorado Regions. In fact, the Pacific Northwest is the only region in the western United States that at present appears to have a water surplus.

The effects of scenarios 1 (warmer and drier) and 2 (cooler and wetter) on the present surface water supply is summarized in Table 31 . Here we show the present regional mean annual supply - which includes inflow from other regions as well as runoff from the particular region and imports of water but not ground water reserves - and the mean annual requirements including water consumed, that lost to evapotranspiration and imported water. These mean annual requirement values are projected to the year 2000. The ratio of requirements to supply is computed for each region. A value of 1.00 indicates requirements are equal to supply. A value in excess of 1.00 indicates the requirements are in excess of supply. As of the year 2000, assuming no climatic change, in only one region, the Lower Colorado, will the requirement/supply ratio exceed 1.0. However, the Rio Grande and Upper Colorado Regions will have requirements approaching supply as the requirement/supply ratios will be 0.87 and 0.84 respectively. The next highest values are for the Missouri and California Regions with a ratio of 0.42 followed by the Texas-Gulf Region with 0.34 and the Great Basin with 0.31. The relatively large surface water storage capacities in these regions will be effective if the projected requirements are realized.

When the same ratios of mean annual requirement/mean annual supply

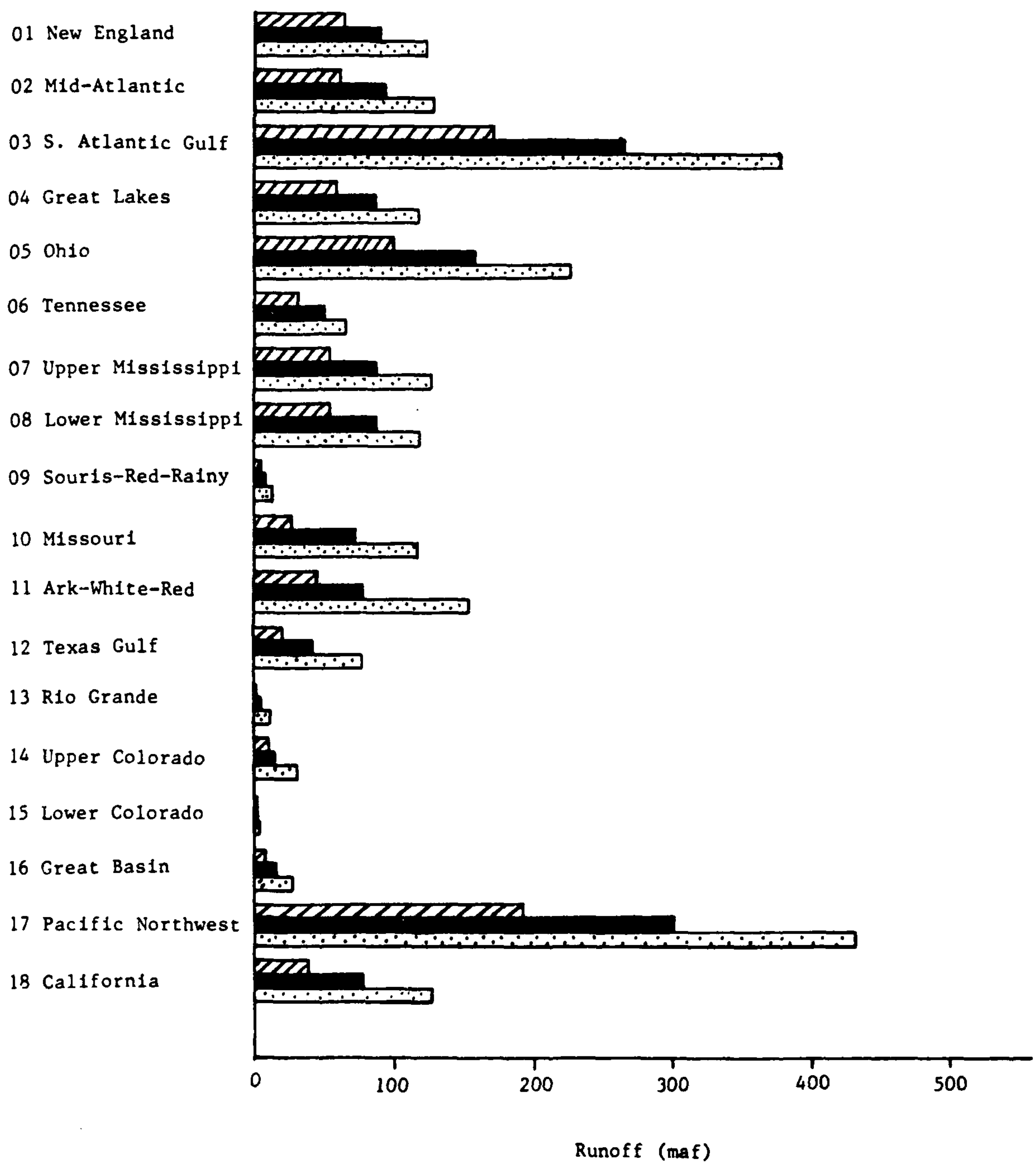


Figure 55. Graph of estimated mean annual runoff from each region for climatic scenario 1 (stripped bar), present (shadow bar) and climatic scenario 2 (dotted bar).

Comparison of requirement/supply ratios for the present climatic state and for warmer and drier (scenario 1) and cooler and wetter (scenario 2) changes.

Region	Present Climatic State			Scenario 1 (warmer and drier)		Scenario 2 (cooler and wetter)	
	Estimated mean annual supply (bgd)[a]	Estimated mean annual requirement (bgd)[c]	requirement / supply	Estimated mean annual supply (bgd)	requirement[e] / supply	Estimated mean annual supply (bgd)	requirement / supply
01 New England	78.6	1.06	0.01	56.6	0.02	108.5	0.009
02 Mid-Atlantic	81.0	3.54	0.04	53.5	0.07	115.0	0.03
03 South Atlantic Gulf	232.5	10.05	0.04	148.8	0.07	339.5	0.03
04 Great Lakes	75.3	4.69	0.06	50.5	0.09	103.2	0.04
05 Ohio	179.0[b]	4.33	0.02	111.0	0.04	256.0	0.02
06 Tennessee	41.1	1.11	0.03	25.9	0.04	56.7	0.02
07 Upper Mississippi	114.0[b]	2.69	0.02	70.7	0.04	166.4	0.02
08 Lower Mississippi	416.8[b]	5.51	0.01	291.8	0.02	571.0	0.009
09 Souris-Red-Rainy	6.1	0.47	0.07	3.4	0.14	10.2	0.05
10 Missouri	61.5	26.14	0.42	22.1	1.18	100.9	0.26
11 Arkansas-White-Red	67.7	12.03	0.18	31.1	0.39	138.8	0.09
12 Texas Gulf	35.6	12.52	0.34	17.8	0.70	71.2	0.18
13 Rio Grande	5.3	4.85	0.87	1.3	3.69	9.5	0.51
14 Upper Colorado	13.9	11.75[d]	0.84	9.3	1.26	27.0	0.44
15 Lower Colorado	8.3[b]	9.87	1.18	3.6	2.74	14.1	0.70
16 Great Basin	13.9	4.37	0.31	7.6	0.57	25.3	0.17
17 Pacific Northwest	286.5	17.28	0.06	171.8	0.10	386.6	0.04
18 California	73.4	30.39	0.42	41.1	0.74	119.6	0.25

(a) assumes zero ground water overdraft
(b) inflow from upstream region included
(c) projected through the year 2000
(d) includes 6.70 bgd for downstream obligations
(e) assumes no increase in evaporation rate from present climatic state

Region	Scenario 1 (warmer and drier)	Scenario 2 (cooler and wetter)
01 New England	-17	-4
02 Mid-Atlantic	-25	4
03 S. Atlantic Gulf	-6	-5
04 Great Lakes	-23	9
05 Ohio	-18	13
06 Tennessee	-24	18
07 Upper Mississippi	-22	11
08 Lower Mississippi	-10	-2
09 Souris-Red-Rainy	-14	5
10 Missouri	-28	12
11 Arkansas-White-Red	-34	21
12 Texas Gulf	-34	21
13 Rio Grande	-33	23
14 Upper Colorado	-34	18
15 Lower Colorado	-35	22
16 Great Basin	-10	-2
17 Pacific Northwest	-18	4
18 California	-34	25

Table 32. Total weights from the speculative impact matrices for each region and scenarios 1 and 2.

are estimated for the climatic change scenarios it is apparent that the semi-arid regions would be most affected by either change. Based on this ratio, scenario 1 (warmer and drier) would have the greatest effect on the Rio Grande, Lower Colorado, Upper Colorado, Missouri, California, Texas-Gulf, Great Basin and Arkansas-White-Red Regions. In those regions where present ground water production is not large, such as the Great Basin, increased use of this resource could compensate for the reduced supply of surface water. However in regions such as the Lower Colorado, Missouri, Arkansas-White-Red and Texas Gulf where ground water is already extensively used, the impact of a warmer-drier (scenario 1) climate would be far more severe.

As one would expect, the occurrence of a cooler and wetter climate (scenario 2) would be most beneficial in the regions adversely affected by a scenario 1 change. In fact the mean annual requirement/mean annual supply ratio would be less than 1.00 for all regions. The highest is 0.70 (Lower Colorado Region) but is substantially less than the 2.74 under a scenario 1 change or the 1.18 value for the present climatic state. The ratio for the New England and Lower Mississippi Regions becomes quite small, 0.009, indicating a large surface water excess and large scale flooding problems. The same applies for the Ohio, Tennessee, Upper Mississippi, Mid-Atlantic and South Atlantic-Gulf Regions.

The impact analysis, however, includes factors other than surface water supply. One can see by inspecting the speculative impact matrices that items such as ground water supply, water quantity, system reliability and cost of operation are also considered in the final impact survey.

According to our speculative impact analyses, all region would be adversely affected by a scenario 1 climatic change (Table 32). The regional average is -23. This implies the reduced runoff associated with the change would have at least some adverse effects on portions of the water resources system in almost every region. In one region, the South Atlantic-Gulf, the impact is considered negligible. The adverse impacts were considered minor in six regions, moderate in five and major in six additional regions (Table 33).

Some of the numerical evaluations shown in Table 32, especially for scenario 1 conditions, may appear to be excessive when compared to the requirement/supply ratio analysis just discussed. For instance, the Lower Mississippi Region, with its humid climate, was assigned a -10 indicating at least minor adverse impact. This is partly due to the fact that streamflow in this region depends to a large extent on inflow from other regions (Upper Mississippi, Missouri, Ohio, Tennessee, Arkansas-White-Red) and this is difficult to assess in the impact matrix. Thus the Lower Mississippi Region would probably be more severely affected, in reality, by extra-regional rather than intra-regional conditions.

At the other extreme, the Great Basin, with a semi-arid climate, also received a -10 for scenario 1 conditions. This is due to the large amounts of ground water available for use and relatively low water demand,

Scenario 1 - All Regions Adversely Affected

Negligible	Minor	Moderate	Major
S. Atlantic Gulf	New England	Mid-Atlantic	Arkansas-White-Red
	Ohio	Great Lakes	Texas Gulf
	Souris-Red-Rainy	Tennessee	Rio Grande
	Great Basin	Upper Mississippi	Upper Colorado
	Pacific NW		Lower Colorado
	Lower Mississippi		California
			Missouri

Scenario 2 - Regions Adversely and Beneficially Affected

Adverse	Beneficial		
Negligible	Negligible	Minor	Moderate
S. Atlantic Gulf	New England	Ohio	Arkansas-White-Red
Lower Mississippi	Mid Atlantic	Tennessee	Texas Gulf
Great Basin	Great Lakes	Upper Mississippi	Rio Grande
New England	Souris-Red-Rainy	Missouri	Lower Colorado
	Pacific NW	Upper Colorado	California

Table 33. Classification of each region by intensity of impacts for climatic changes as described by scenarios 1 and 2.

both now and for the year 2000.

Also, under arid conditions, the Lower Colorado Region was assigned a -35 rating, the highest of any region for scenario 1 conditions. Runoff within the region contributes relatively little to the flow of the Colorado River in contrast to that which comes from the Upper Colorado River Region. In contrast to the Great Basin, available ground water supplies are already being extensively mined and there would be little available to supplement reduced withdrawals from the Colorado River.

For scenario 2, adverse effects are predicted for some regions although the National impact would be mostly beneficial with an average regional beneficial rating of +11. The adversely affected regions are the South Atlantic-Gulf, the New England, the Lower Mississippi and the Great Basin. In the first three cases, the regions are presently water-rich (in the case of the Lower Mississippi because of large inflow) and additional runoff would probably be adverse rather than beneficial. In the Great Basin with its large closed basins, it is assumed the additional runoff would cause inundation of large areas. The remaining 15 regions would be beneficially affected although five of these fall into the negligible category. These four are the Mid-Atlantic, Great Lakes, Souris-Red-Rainy and the Pacific Northwest Regions. An appreciable impact would be felt by ten regions, although four of these would experience increased flooding. The 18 regions have been grouped according to relative influence on each of the climatic change scenarios and the results are shown in Table 33.

Several regions would experience only negligible or minor impacts regardless of whether scenario 1 or 2 occurred. These include New England, South Atlantic-Gulf, Ohio, Souris-Red-Rainy, Great Basin and Pacific Northwest. In all of these regions water is currently abundant and although occurrence of climatic change might create hardships, the result would not be catastrophic on a region-wide basis. But in the Arkansas-White-Red, Texas Gulf, Rio Grande, Upper Colorado, Lower Colorado, California and Missouri Regions, the occurrence of a scenario 1 type change would possibly create region-wide economic and legal havoc and would certainly have national policy implications. A perspective of the national policy implications can be gained by noting the recent national attention given to the 1975-77 drought in the western United States. Much was said about dwindling reservoir supplies and in fact many areas in northern California were subjected to severe rationing (in San Francisco, water was limited to 37 gallons per day per person).

The effects of the climatic change scenarios on the total surface water reserve can be shown by the ratios of total reservoir capacity to mean annual runoff. This has been done for the present total regional reservoir capacity and the present mean annual runoff and also for estimated mean annual runoff under climatic change scenarios 1 and 2. Total capacity was used so that both scenarios could be compared to the same storage capacity. Table 34 shows the ratio of total regional capacity to present mean annual regional runoff, and the comparable ratios assuming the occurrence of climatic change as described by scenarios 1 and 2. The results show that,

Region	Ratio Present	Scenario 1	Scenario 2
01 New England	0.384	0.537	0.280
02 Mid-Atlantic	0.481	0 728	0.343
03 South Atlantic Gulf	0.391	0.421	0.189
04 Great Lakes	0.273	0.407	0.199
05 Ohio	0.379	0.612	0.264
	(0.293)	(0.471)[1]	(0.206)[1]
06 Tennessee	0.754	1.198	0.547
07 Upper Mississippi	0.425	0.686	0.291
	(0.269)	(0.513)[1]	(0.176)[1]
08 Lower Mississippi	0.308	0.440	0.225
	(0.053)	(0.089)[1]	(0.035)[1]
09 Souris-Red-Rainy	1.723	3.116	1.030
10 Missouri	2.923	8.120	1.771
11 Arkansas-White-Red	1.320	2.413	0.662
12 Texas Gulf	1.966	3.942	1.046
13 Rio Grande	3.580	14.200	1.991
14 Upper Colorado	1.378	2.208	0.718
15 Lower Colorado	(12.658)	(18.988)[1,2]	(4.830)[1,2]
16 Great Basin	0.512	0.930	0.286
17 Pacific Northwest	0.399	0.625	0.277
18 California	1.078	2.155	0.633

()indicates inflow taken into account when ratio is computed.

1 Assuming percentage of mean annual runoff consumed in contributing basins remains constant.

2 Assuming percentage of mean annual runoff available for use is the same as at present.

TABLE 34. Ratio of total available storage to mean annual runoff for each region, computed for present and Scenarios 1 and 2.

except for the Tennessee Region, all regions east of and including the Mississippi River would tend to fill the existing reservoir storage in less than one year regardless of whether scenario 1 or 2 climatic changes occurred. In the west, the region most effected by either change would be the Lower Colorado River Region. Under the present climatic regime and total available storage, there is enough capacity to accomodate 12+ years of mean annual regional flow including the present level of inflow. If a scenario 1 type change occurred, it would require nearly 19 years to fill the presently available total storage. A scenario 2 type change would require a little less than 5 years of mean flow to fill the present reservoir capacity. The severe impact a scenario 1 type change would have on the Rio Grande Region is also apparent. Present total storage capacity will accomodate a little over 3½ years of mean flow under the present climate, but if a scenario 1 type change would occur, a little over 14 years of mean flow would be required to fill the present total capacity. A scenario 2 type change would require only a little less than 2 years. In the Missouri Region, the large present total reservoir capacity would be quite beneficial as only a little less than two years of mean flow would be required to fill to total capacity; presently a little less than 3 years is required. If a scenario 1 type change occurred, a little over 8 years would be necessary.

A similar conclusion is reached based on a region-by-region comparison of the Q_{05}/Q_{95} ratio. This ratio represents a measure of streamflow variability from each of the regions. One would anticipate that the higher the value, the less storage controls outflow and the more sensitive the region would be to climatic variation. The interregional comparison of these values is shown in Table 35. The six largest values are for the Rio Grande, Texas-Gulf, Arkansas-White-Red, Missouri, Upper Colorado and California Regions. These compare favorably with the regions ranked as being most seriously affected by a scenario 1 (warmer and drier) climatic change in Table 33. The exceptions are the Missouri and Lower Colorado River Basins. The Missouri Region is ranked as being moderately affected by a warmer-drier climate (Table 33), just one category below the other five regions. In contrast, the Lower Colorado is so controlled (consequently the 1.4 ratio) that the annual runoff is actually negative due to excessive evapotranspiration. This fact, when compared to the large demand makes the Q_{05}/Q_{95} ratio unrealistic when evaluating the climatic impact for this region. The remaining regions compare reasonably well with moderate to minor rankings of the impact matrices.

In the area west of the Mississippi River, a scenario 1 type change would probably require additional reservoir construction although in some regions, the present capacity appears to be excessive. The latter is especially true in arid regions such as the Rio Grande and Lower Colorado where the total flow is essentially allocated. Hence the construction of more impoundments would likely result in increased evaporation and bank storage to the point where the amount of water available for use would be decreased. In the regions east of and including the Upper and Lower Mississippi Regions, the mean regional flow resulting from a scenario 2 type change would tend to fill the total reservoir storage in about ½ the time required for the present mean annual flow. It appears that (should

	Region	Q_{05}/Q_{95} *	Rank (Highest is #1)
01	New England	2.2	14
02	Mid-Atlantic	2.4	12
03	South Atlantic-Gulf	2.9	9
04	Great Lakes	2.3	13
05	Ohio	2.4	11
06	Tennessee	1.9	15
07	Upper Mississippi	2.9	10
08	Lower Mississippi	3.7	8
09	Souris-Red-Rainy	1.4	17
10	Missouri	4.1	4
11	Arkansas-White-Red	5.5	3
12	Texas-Gulf	10.3	2
13	Rio Grande	22.0	1
14	Upper Colorado	4.0	5
15	Lower Colorado	1.4	18
16	Great Basin	3.8	7
17	Pacific Northwest	1.9	16
18	California	4.0	6

$* \dfrac{\text{flow exceeded 5 out of 100 years}}{\text{flow exceeded 95 out of 100 years}}$

Table 35. Comparison of Q_{05}/Q_{95} values for each of the 18 regions.

such a climatic change occur) much additional storage would be needed in these regions primarily for flood control.

Projected Climatic Trends

On a hemispherical scale, there is rather conclusive evidence that the mean annual temperature is cooling (Van Loon and Williams, 1976). Recent work by Kukla et al (1977) indicates this trend has not abated. They conclude from analysis of several variables including surface air temperature, upper atmosphere temperature, sea surface temperature, and relative area of snow on land and relative abundance of pack ice, that from 1950-1975, the rate of cooling for most of the above climatic indices in the northern hemisphere was between 0.1° and 1.2°C. per decade. However, the slope of the changes versus time curve for most of the indices from the middle and low latitudes of the northern hemisphere increased during the interval 1971-1975. In the higher latitudes, the slope decreased or reversed. Peterson and Lawson (1978) using isotopic paleotemperature data and Box-Jenkins modeling to obtain a forecasting equation, predict an expected mean annual temperature decrease for the northern hemisphere of about 1.3°C. (With 95% confidence limits of -0.1 and -2.4) over the next 5000 years. The point is, there appear to be different lines of evidence suggesting a present cooling trend with at least one study suggesting it will continue.

Analysis of the individual regional runoff series do not show any indication of trends in runoff data suggesting a uniform increase in annual runoff. In fact the opposite is true, in a rather restricted segment of the western southern-intermountain region (see for example the previous sections for the Rio Grande and Upper Colorado Regions), the trend is toward reduced runoff. This same trend is apparent in precipitation trends, especially winter (Bradley, 1976) and in tree-ring data from the area primarily representative of winter and spring precipitation. Langbein, unpublished data, shows a general trend toward decreasing annual streamflow in the West, (Figure 56) with a marked decrease when only the western southern-intermountain region is considered. The evidence is strong that this is the result of decreased annual winter precipitation. When the overall total streamflow of the Nation is considered (Figure 57) however, there is no apparent trend in the data.

The region-by-region evaluation shows that on a national basis, a scenario 2 type change would be mostly beneficial. There exists certain climatic evidence that the future most likely change would be more like scenario 2 than scenario 1; however, the only significant trends in streamflow that can be attributed to climate, those in the southern intermountain West are more like those projected under the assumption of a scenario 1 type change.

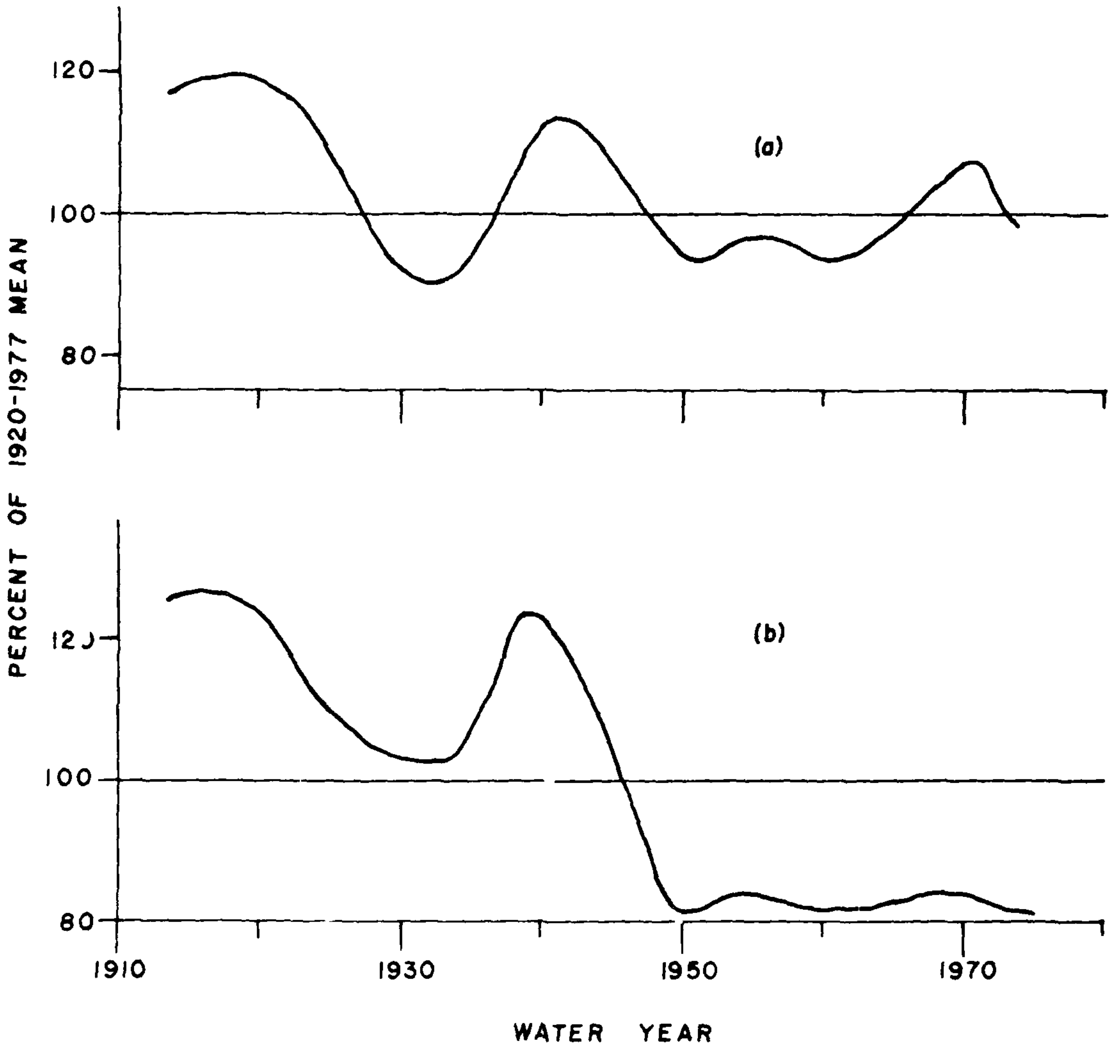


Figure 56. Ten year moving averages of ratios of yearly streamflow to average for 1920-1977 for selected stations in (a) the Western United States and for (b) the Southern intermountain area of the West (after Langbein, unpublished).

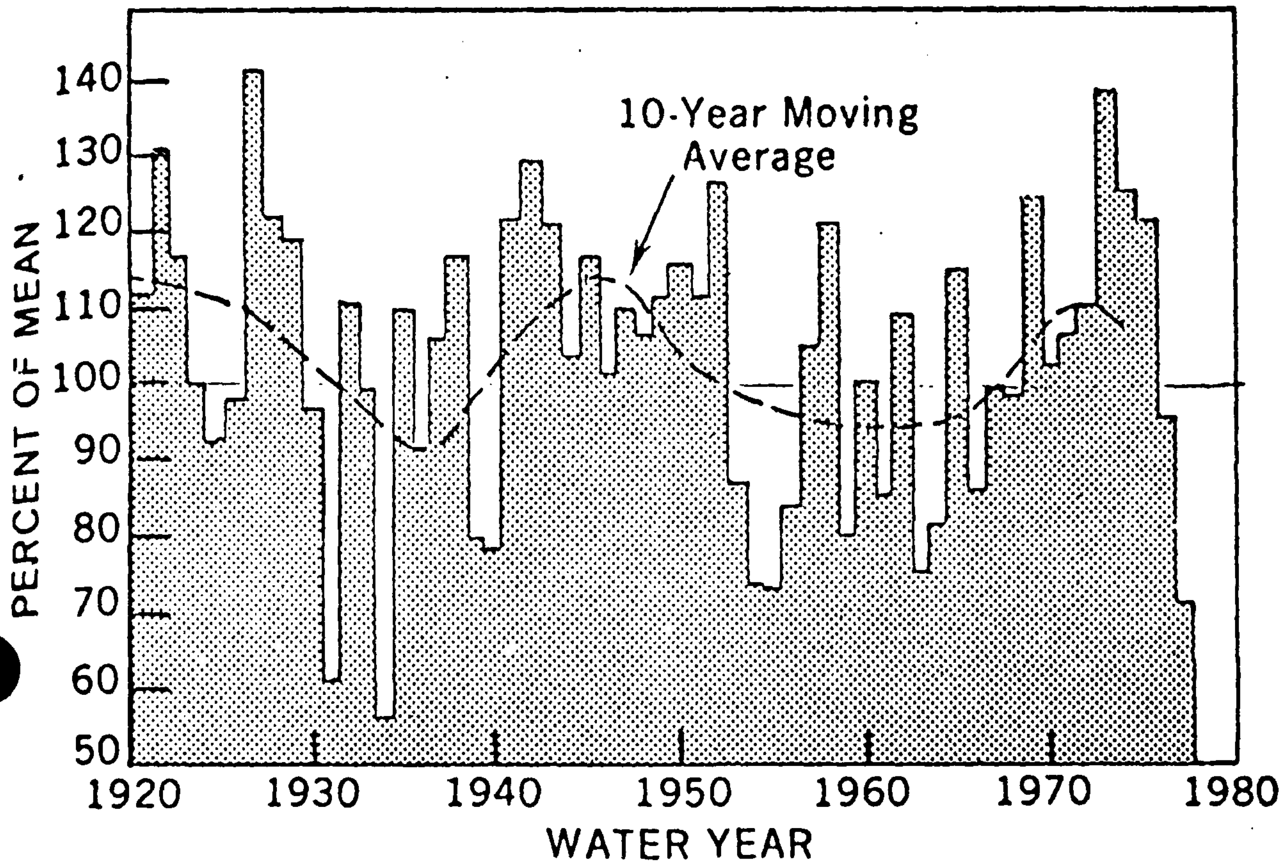


Figure 57. Average of selected streamflow records showing individual year percentages of mean flow for the period 1900-1977. Note the trend that is apparent in the western records (Figure 56) is not evident (after Langbein, U.S.G.S. press release, March 12, 1978).

LITERATURE CITED

Anderson, M. G., 1975. Demodulation of streamflow series. Journal of Hydrology, 26: 115-121.

Antevs, Ernst, 1938. Rainfall and tree growth in the Great Basin. Am. Geos. Soc. Spec. Publ. 21, 97 pp.

Asakura, H., 1975. Unpublished data from NAS.

Baker, E. T. and J. R. Wall, 1976. Summary appraisals of the nation's ground water resources - Texas Gulf region. U. S. Geol. Survey Prof. Paper 813-F, 29 pp.

Beard, L. R., 1962. Statistical methods in hydrology. U. S. Army Engineer District, Corps of Engineers, Sacramento, California.

Beard, L. R., 1972. Hydrologic data management. Reports on Hydrologic Engineering Methods for Water Resources Development, Vol. 2. U. S. Army corps of Engineers.

Bedinger, M. S. and R. T. Sniegocki, 1976. Summary appraisals of the nation's ground water resources - Arkansas-White-Red region. U. S. Geol. Survey Prof. Paper 813-H, 31 pp.

Beltzner, Klaus (editor), 1976. Living with Climatic Change. Proceedings, Toronto Conferenee Workshop Nov. 17-22, 1975. Science Council of Canada, Ottawa, 105 pp.

Blackman, R. B. and J. W. Tukey, 1958. The Measurement of Power Spectra: From the Point of View of Communications Engineering. Dover Publ., Inc., New York, 190 pp.

Bloomfield, Peter, 1976. Fourier Analysis of Time Series: an Introduction. John Wiley and Sons, Inc., New York, 258 pp.

Bloyd, R. M., Jr., 1974. Summary appraisals of the nation's ground water resources - Ohio region. U. S. Geol. Survey Prof. Paper 813-A, 41 pp.

Bloyd, R. M., Jr., 1975. Summary appraisals of the nation's ground water resources - Upper Mississippi region. U. S. Geol. Survey Prof. Paper 813-B, 22 pp.

Box, George E., and Gwilym M. Jenkins, 1976. Time Series Analysis Forecasting and Control. Revised edition, Holden-Day, San Francisco, 575 pp.

Bradley, R. S., 1976. Precipitation History of the Rocky Mountain States. Westview Press, Boulder, Colorado.

Bryson, R. A. and F. Kenneth Hare, 1974. The climates of North America. In World Survey of Climatology, Vol. 2. Elsevier Scientific Publ. Co., New York, 1-47.

Budyko, M. I., 1969. The effect of solar radiation variations on the climate of the earth. Tellus, 21: 611-619.

Burges, Stephen J. and Dennis P. Lettenmaier, 1977. Comparison of annual streamflow models. Journal of the Hydraulics Division, HY9: 991-1006.

Delleur, J. W., P. C. Tao and M. L. Kavvas, 1976. An evaluation of the practicality and complexity of some rainfall and runoff time series models. Water Resources Res., 12(5): 953-970.

Ditlevsen, Ove., 1971. Extremes and first passage times with application in civil engineering. Tech. Report, Univ. of Denmark, Copenhagen.

Dooge, James C. I., 1973. Linear theory of hydrologic systems. Tech. Bull. No. 1468, Agric. Res. Service, U. S. Dept. of Agriculture.

Dzerdzeevskii, B., 1962. Fluctuations of climate and of general circulation of the atmosphere in extra-tropical latitudes of the Northern Hemisphere and some problems of dynamic climatology. Tellus, 14:328-336.

Eagleston, Peter S., 1978. Climate, soil, vegetation (in 7 parts). Water Resources Res., 14(5): 705-776.

Eakin, T. E., D. Price and J. R. Harrill, 1976. Summary appraisals of the nation's ground water resources - Great Basin region. U. S. Geol. Survey Prof. Paper 813-G, 37 pp.

Freeze, R. A., 1972. Role of subsurface flow in generating surface runoff: 1. Baseflow contributions to channel flow. Water Resources Res., 8(3): 601-623.

Fritts, J. C., 1976. Tree Rings and Climate. Academic Press, London, New York, San Francisco, 567 pp.

Fritts, H. C. and G. R. Lofgren, 1978. Patterns of climatic change revealed through dendroclimatology. Contract report to U. S. Army Coastal Engineering Research Center, No. DACW 72-78-0046, 69 pp.

Gatewood, J. S., A. Wilson, H. E. Thomas and L. R. Kister, 1964. General effects of drought on water resources of the Southwest. U. S. Geol. Survey Prof. Paper 372-B, 31-36.

Gomide, F. L. S., 1978. Markovian inputs and the Hurst phenomenon. Journal of Hydrology, 37: 33-47.

Granger, Clive W. J. and Daniel Orr, 1972. "Infinite variance" and research strategy in time series analysis. Journal of the American Statistical Association, 67(338): 275-285.

Hardman, George and O. E. Reil 1936. The relationship between tree-growth and stream runoff in the Truckee River Basin, California-Nevada. Univ. Nevada Ag. Expt. Sta. Bu.. 141, 38 pp.

Hasselman, K., 1976. Stochastic climate models: Part 1. Theory. Tellus, 28(6): 473-484.

Hays, J. D., John Imbrie and N. J. Shackleton, 1976. Variations in the earth's orbit: pacemaker of the ice ages. Science, 194: 1121-1132.

Hipel, K. W., 1975. Contemporary Box-Jenkins modeling in hydrology. Ph. D. thesis, Univ. of Waterloo, Waterloo, Ontario, Canada.

Hipel, K. W., A. I. McLeod, and W. C. Lennox, 1977. Advances in Box-Jenkins modeling: 1. Model construction. Water Resources Res., 13(3): 567-575.

Hirschboeck, Katherine K., 1976. The general circulation of the atmosphere and precipitation in the Southwest: Some implications for paleoecological studies. Unpublished paper, Dept. of Geosciences, Univ. of Arizona.

Hoyt, W. G. and W. B. Langbein, 1944. The yield of streams as a measure of climatic fluctuations. Geographical Review, 32(2): 218-234.

Hurst, H. E., 1957. A suggested statistical model of some time series which occur in nature. Nature, 180: 494.

Hurst, H. E., R. P. Black and Y. M. Simaika, 1965. Long-term Storage: an Experimental Study.

Inter-Agency Committee on Water Resources, 1966. Methods of flow frequency analysis: notes on hydrologic activities. Bulletin No. 13, U. S. Gov't Printing Office, Washington, D. C.

Irons, W. V., C. H. Hembree and G. L. Oakland, 1965. Water resources of the Upper Colorado river basin - technical report. U. S. Geol. Survey Prof. Paper 441.

Jenkins, G. M. and D. G. Watts, 1968. Spectral Analysis and its Applications. Holden-Day, San Francisco, 525 pp.

Julian, Paul R., 1970. An application of rank-order statistics to the joint spatial and temporal variations of meteorological elements. Monthly Weather Review, 98(2): 142-153.

Kapteyn, J.C., 1914. Tree-growth and meteorological factors. Recueil des Travaux Botaniques Neerlandais, 11: 71-93. (Cited in Schulman, 1945b, p. 6).

Keen, F. P., 1937. Climatic cycles in eastern Oregon as indicated by tree-rings. Monthly Weather Review, 65(5): 175-188.

Kilmartin, Ronald F., 1976. Hydroclimatology -- a needed cross-discipline. Paper presented at Fall Conference, American Geophysical Union, San Francisco, California, December, 1976.

Klemes, V., 1974. The Hurst phenomenon: a puzzle? Water Resources Res., 10(4): 175-188.

Kraus, Dr. E. B., 1958. Recent climatic changes. Nature, 181: 666-668.

Kutzbach, J. E. and R. A. Bryson, 1975. Variance spectrum of holocene climatic fluctuations in the North American sector. In Proceedings of the WMO/IAMAP Symposium on Long-term Climatic Fluctuations, Geneva, Switzerland, WMO Publ. No. 421: 97-103.

Ladurie, E. LeR., 1971. Times of Feast and Times of Famine: a History of Climate Since the Year 1000. Double Day, Garden City, New York.

LaMarche, Valmore C., Jr., 1973. Holocene climatic variations inferred from treeline fluctuations in the White Mountains, California. Qartenary Res., 3(4): 632-660.

Lamb, H. H., 1975. Remarks on the current climatic trend and its perspective. In Proceedings of the WMO/IAMAP Symposium on Long-term Climatic Fluctuations, Geneva, Switzerland, WMO Publ. No. 421: 473-477.

Lamb, H. H., 1977. Climate: Present, Past and Future: Vol. 2, Climatic History and the Future. Meuthen and Co., Ltd., London.

Langbein, W. B., 1978. Press Release, U. S. Geol. Survey.

Langbein, W. B. and others,1949. Annual runoff in the United States. Geol. Survey Circular 5, U. S. Dept. of the Interior, Washington, D. C., June 1949, Reprinted 1959.

Langbein, W. B. and J. V. B. Wells, 1955. The water in the rivers and creeks. In Water, the Yearbook of Agriculture, 1955. U. S. D. A., Sup. of Documents, Gov't. Printing Office, Washington, D. C., pp. 52-62.

Lettenmaier, Dennis P. and Stephen J. Burges, 1977a. Operational assessment of hydrologic models of long-term persistence. Water Resources Res., 13(1): 113-124.

Lettenmaier, Dennis P. and Stephen J. Burges, 1977b. An operational approach to preserving skew in hydrologic models of long-term persistence. Water Resources Res., 13(2): 281-290.

Lettenmaier, Dennis P, and Stephen J. Burges, 1978. Climatic change: Detection and its impact on hydrologic design. Water Resources Res., 14(1): 679-687.

Lorenz, E. M., 1970. Climatic change as a mathematical problem. Journal of Applied Meteorology, 9: 325-529.

Mandelbrot, B. B., 1971. A fact fractional Gaussian noise generator. Water Resources Res., 7: 543-553.

Mandelbrot, Benoit B., 1977. Fractals: Form, Chance and Dimension. W. H. Freeman and Co., San Francisco.

Mandelbrot, B. B. and James R. Wallis, 1968. Noah, Joseph and operational hydrology. Water Resources Res., 4(5): 909-918.

Mandelbrot, B. B. and J. R. Wallis, 1969. Some long-run properties of geophysical records. Water Resources Res., 5(2): 321-340.

Mandelbrot, B. B. and J. R. Wallis, 1969a. Computer experiments with fractional Gaussian noises. Water Resources Res., 5(1): 228-267.

Mandelbrot, B. B. and J. R. Wallis, 1969b. Robustness of the rescaled range R/S in the measurement of noncyclic long-run statistical dependence. Water Resources Res., 5(5): 967-988

Matalas, N. C. and J. R. Wallis, 1971. Statistical properties of multivariate fractional noise processes. Water Resources Res., 7(6): 1460-1468.

McGuinness, C. L., 1963. The role of ground water in the national water situation. U. S. Geol. Survey Water Supply Paper 1800, 1121 pp.

McLeod, Angus Ian, Keith W. Hipel and W. C. Lennox, 1977. Advances in Box-Jenkins modeling: 2. Applications. Water Resources Res., 13(3): 577-586.

Mejia, J. M., D. R. Dawdy and C. F. Nordin, 1974. Streamflow simualtions: 3. The broken line process and operational hydrology. Water Resources Res., 8: 931.

Mitchell, J. M., 1961. Recent secular changes of global temperature. Ann. New York Academy of Science, 95(1); 235-250.

Mitchell, V. L., 1969. The regionalization of climate in montane areas. Ph. D. thesis, Univ. of Wisconsin, Madison, 147 pp.

Muller, Robert A., Principal Academic Advisor, 1974. Physical Geography Today - a Portrait of a Planet. CMR Books, Del Mar, California.

National Research Council, U. S. Committee for the Global Atmospheric Research Program, 1975. Understanding Climatic Change - a Program for Action. National Academy of Sciences, Washington, D. C.

National Research Council, Panel on Water and Climate, 1977. Studies in Geophysics: Climate, Climatic Change and Water Supply. Printing and Publishing Office, National Academy of Sciences. Washington, D. C.

O'Connell, Patrick E., 1974. Stochastic modeling of long-term persistence in streamflow sequences. Ph.D. thesis, Imperial College, University of London, 284 pp.

O'Connell, Patrick E., 1977. ARIMA models in synthetic hydrology. In Mathematical Models for Surface Water Hydrology. John Wiley and Sons, London, New York, Sydmey, Toronto.

Palmer, W. C., 1965. Meteorological drought. U. S. Weather Bureau Research Paper 45, U. S. Dept. of Commerce, Washington, D. C, 58 pp.

Peterson, E. L. and S. E. Larsen, 1978. A statistical study of a composite isotopic paleotemperature series from the last 700,000 years. Tellus, 30: 193-200.

Potter, Kenneth W., 1976. Evidence for nonstationarity as a physical explanation of the Hurst phenomenon. Water Resources Res., 12(5): 1047-1052.

Potts, H. L., 1962. A six hundred year record of drouth recurrences. Paper presented at the First Water Resources Engineering Conference, Am. Soc. Civil Engineers, May 18, 1962, Omaha, Nebraska.

Price, C. and T. Arnow, 1974. Summary appraisals of the nation's ground water resources - Upper Colorado region. U. S. Geol. Survey Prof. Paper 813-C, 40 pp.

Reeder, H. O., 1978. Summary appraisals of the nation's ground water resources - Souris-Red-Rainy region. U. S. Geol. Survey Prof. Paper 813-K, 25 pp.

Rodriguez-Iturbe, I., D. R. Dawdy and L. E. Garcia, 1971. Adequacy of Markovian models with cyclical components for stochastic streamflow simulation. Water Resources Res., 7(5): 1127-1143.

Rodriguez-Iturbe, I., J. M. Mejia and D. R. Dawdy, 1972. Streamflow simulations: 1. A new look ar Markovian models, fractional Gaussian noise and crossing theory. Water Resources Res., 8(4): 921-974.

Schulman, Edmund, 1945a. Runoff histories in tree-rings of the Pacific slope. The Geographic Review, 35(1): 59-73.

Schulman, Edmund, 1945b. Tree-ring hydrology of the Colorado River basin. Univ. of Arizona Bull. 16(4), (Lab. of Tree-Ring Res. Bull. 4), p. 36.

Schulman, Edmund, 1947. Tree-ring hydrology in southern California. Univ. of Arizona Bull. 18(3), (Lab. of Tree-Ring Res. Bull. 4), p. 36.

Schulman, Edmund, 1951. Tree-ring indices of rainfall, temperature and river flow. In Compendium of Meteorology, Boston, Am. Meteorol. Soc., p. 1024-1029.

Schwarz, H. E., 1977. Climatic change and water supply: how sensitive is the Northeast? In Studies in Geophysics, Climate, Climatic Change and Water Supply. The National Research Council, National Academy of Sciences, Washington, D. C.

Seyhan, Dr. I. Erisn, 1977. The watershed as a hydrologic unit. Geografisch Instituut, Transitorium II, Heidelberglaan 2, Utrecht, Nederlans.

Sinnott, A. and E. Cushing, 1978. Summary appraisals of the nation's ground water resources - Mid-Atlantic region. U. S. Geol. Survey Prof. Paper 813-I, 32 pp.

Srikanthan, R. and T. A. McMahon, 1978. A review of lag-one Markov models for generation of annual flow. Journal of Hydrology, 37(1978): 1-12.

Stockton, Charles W., 1977. Interpretation of past climatic variability from paleoenvironmental indicators. In Studies in Geophysics: Climate Climatic Change and Water Supply. The National Research Council, National Academy of Sciences, Washington, D. C.

Stockton, Charles W. and Gordon C. Jacoby, Jr., 1976. Long-term surface water supply and streamflow trends in the Upper Colorado River basin. Lake Powell Research Project Bull. 18, National Science Foundation.

Thomas, H. E. and D. A. Phoenix, 1976. Summary appraisals of the nation's ground water resources - California region. U. S. Geol. Survey Prof. Paper 813-E, 54 pp.

Thornthwaite, C. W., 1948. An approach toward a rational classification of climate. Geographical Review, 38: 55-94.

Thornthwaite, C. W. and J. R. Mather, 1955. The water balance. Drexel Inst. Tech. Publ. Climatology, 8(1): 1-104, Centerton, N. J.

Todini, Ezio and James R. Wallis, 1977. Using CLS for daily or longer period rainfall runoff modeling. In Mathematical Models for Surface Water Hydrology. John Wiley and Sons, London, New York, Sydney, Toronto.

United States Water Resources Council, 1977. Guidelines for determining floodflow frequency. Bull. 17-A of the Hydrology Committee, U. S. Water Resources Council, Washington, D. C. (Revised 1977).

United States Water Resources Council, 1978. The Nation's Water Resources -- the Second National Water Assessment by the U. S. Water Resources Council, U. S. Water Res. Coun., Washington, D. C.

van Loon, Harry and Jill Williams, 1976. The connection between trends of mean temperature and circulation at the surface: Part 1. Winter. Monthly Weather Review, 104: 365-380.

Wahl, E. W. , 1968. A comparison of the climate of the Eastern U. S. during the 1830's with the current normals. Monthly Weather Review, 96:73-82.

Wahl, K. H. and T. L. Lawson, 1970. The climate of the mid-nineteenth century United States compared to the current normals. Monthly Weather Review, 98: 259-265.

Wallis, J. R. and N. C. Matalas, 1970. Small sample properties of H and K -- estimators of the Hurst coefficient H. Water Resources Res. 6(6): 1583-1594.

Wallis, J. R. and N. C. Matalas, 1972. Sensitivity of reservoir design to the generating mechanism of inflows. Water Resources Res. 8(3): 634-641.

Wallis, J. R., N. C. Matalas and J. R. Slack, 1974. Just a moment! NTIS, U. S. Dept. of Commerce, PB-231816.

Wallis, J. R. and P. Edna O'Connell, 1973. Firm reservoir yield -- how reliable are historic hydrological records? Hydr. Sci. Bull. XVIII, 39: 347-365.

Weekly Weather and Crop Bulletin, published by the Agricultural Weather Support Service, USDA, Washington, D. C.

Weist, W. G., Jr., 1978. Summary appraisals of the nation's ground water resources - Great Lakes region. U. S. Geol. Survey Prof. Paper 813-J, 30 pp.

West, S. W. and W. L. Broadhurst, 1975. Summary appraisals of the nation's ground water resources - Rio Grande region. U. S. Geol. Survey Prof. Paper 813-D, 39 pp.

World Meteorological Organization (WMO), 1975. Intercomparison of conceptual models used in operational hydrology forecasting. Operational Hydrology Report 7, WMO Publication 429, Geneva.

Zurawski, A., 1978. Summary appraisals of the nation's ground water resources- Tennessee region. U. S. Geol. Survey Prof. Paper 813-L, 35 pp.

APPENDIX

SPECULATION IMPACT MATRICES

Regions 1-18

Appendix Table 1. Region 01, Scenario 1 (Warmer and Drier)

	INCREASE (DECREASE) IN MEAN ANNUAL STREAMFLOW	INCREASE (DECREASE) IN VARIANCE OF STREAMFLOW	INCREASE(DECREASE) SKEWNESS OF DISTRIBUTION OF STREAMFLOW	INCREASE (DECREASE) IN PERSISTENCE OF STREAMFLOW	RAPIDITY & DURATION OF CHANGE IN STREAMFLOW	OVERALL REGIONAL SENSITIVITY TO CLIMATIC VARIATION
Δ YIELD FROM UNREGULATED BASINS	decrease in $\bar{Q}$ annual to about 70 percent of present supply	decrease in baseflow resulting in increased variance	larger number of low flows may increase skew	increase in number of low flow days	little change from present	30 % decrease but probably not great enough to cause region wide shortages -2
Δ YIELD FROM RESERVOIRS	significant decrease	great on smaller reservoirs; small on large reservoirs	small for smaller reservoirs; may be significant for larger reservoirs	may be severe based on size of reservoir	little change from present	may have large effect on individual reservoirs and their use -2
Δ YIELD FROM GROUND WATER SOURCES	decrease but probably not important because of small usage (except where salt water encroachment is prevalent	great effect because of thin aquifers & thin association with stream systems	little change from present	decrease as recharge decreases	little change from present	may be adverse to shallow wells and in areas of salt water encroachment -2
Δ QUALITY OF UNTREATED WATER	large deterioration as inputs steady or increase with decrease in $\bar{Q}$	highly variable depending on change in baseflow component	greater number of low flow days may cause serious water quality problems	persistence in low flows may cause severe pollution problems	little change from present	may deteriorate and cause intense pollution problems -4
EFFECTIVENESS OF INTERBASIN AND INTERSYSTEM CONNECTIONS	some may be inadequate because of decrease in water availability	may prove to be inadequate because of lack of storage	little change from present	may be ineffective if persistence in low flow days is region wide	little change from present	probably not greatly adversely affected -1
ESTIMATED SYSTEM RELIABILITY	present and projected demands are well within scenario changes	may be unreliable locally because of lack of storage	greater number of low flow days may create reliability problems	system may be unreliable because of underdesign for persistence	little change from present	may be unreliable in extended low flow periods -2
MAGNITUDE AND CONTROL OF DEMAND	demand increase in urban areas but by small percentage of total	little change from present	little change from present	demand may increase	little change from present	some increase in demand but region wide small -1
COST OF OPERATION OF WATER SYSTEMS	increased as some local modifications necessary	may be increased as modifications become necessary	no effect	may increase many fold as correction increases are made	little change from present	may be necessary to make changes especially if persistent low flow periods occur -2
ABILITY OF THE WATER SYSTEM TO RESPOND TO CLIMATIC VARIATION	good as present and future projected usage is only 607 of present supply	locally some problems but overall probably no effect	storage may be deficient to handle larger number of low flow days	probably not able to respond adequately; lack of reservoir storage of major concern	little change from present	the overall regional outlook would not be severely affected by this scenario -1

Appendix Table 2. Region 01, Scenario 2 (Cooler and Wetter)

	INCREASE (DECREASE) IN MEAN ANNUAL STREAMFLOW	INCREASE (DECREASE) IN VARIANCE OF STREAMFLOW	INCREASE(DECREASE) SKEWNESS OF DISTRIBUTION OF STREAMFLOW	INCREASE (DECREASE) IN PERSISTENCE OF STREAMFLOW	RAPIDITY & DURATION OF CHANGE IN STREAMFLOW	OVERALL REGIONAL SENSITIVITY TO CLIMATIC VARIATION
Δ YIELD FROM UNREGULATED BASINS	increase to about 135- 140 percent of present flow	may become more variable but not detrimental	probably no change in skew, therefore no effect	increase in high flow frequency would increase yield above that in column (1)	no effect	increased yield but possibly to the point of causing flooding -1
Δ YIELD FROM RESERVOIRS	increase to storage limitations	not affected by increase in variance toward wet side	probably no change in skew, therefore no effect	increase to limit of reservoir	no effect	may increase yield to storage limit leaving no flood storage -2
Δ YIELD FROM GROUND WATER SOURCES	probably unlimited depending on aquifer	no effect	probably no change in skew, therefore no effect	unlimited for shallow aquifers in river valleys	no effect	shallow aquifer yield should improve +2
Δ QUALITY OF UNTREATED WATER	improved, very few low flow periods	no effect	probably no change in skew, therefore no effect	unimproved by increase in high flow frequencies	no effect	surface water should be plentiful to remove wastes +2
EFFECTIVENESS OF INTERBASIN AND INTERSYSTEM CONNECTIONS	no effect	no effect	probably no change in skew, therefore no effect	probably make connections unneeded	no effect	no effect 0
ESTIMATED SYSTEM RELIABILITY	may prove to be inadequate for flood control	storage may not be large enough to adequately handle increase in variance	probably no change in skew, therefore no effect	possibly poor for flood control	no effect	may be unreliable for flood protection -1
MAGNITUDE AND CONTROL OF DEMAND	little or no change from present	little or no change from present	little or no change from present	little or no change from present	little or no change from present	little or no change from present 0
COST OF OPERATION OF WATER SYSTEMS	no effect	no effect	probably no change in skew, therefore no effect	flood damage may become excessively large	no effect	flood damages may increase considerably -2
ABILITY OF THE WATER SYSTEM TO RESPOND TO CLIMATIC VARIATION	may be unable to provide adequate flood protection	may cause problems in flood plain management as frequency distribution of floods change	probably no change in skew, therefore no effect	probably unable to cope with persistent high flow periods	no effect	possibly some adverse effects -2

Appendix Table 3. Region 02, Scenario 1 (Warmer and Drier)

	INCREASE (DECREASE) IN MEAN ANNUAL STREAMFLOW	INCREASE (DECREASE) IN VARIANCE OF STREAMFLOW	INCREASE(DECREASE) SKEWNESS OF DISTRIBUTION OF STREAMFLOW	INCREASE (DECREASE) IN PERSISTENCE OF STREAMFLOW	RAPIDITY & DURATION OF CHANGE IN STREAMFLOW	OVERALL REGIONAL SENSITIVITY TO CLIMATIC VARIATION
Δ YIELD FROM UNREGULATED BASINS	decrease surface water runoff to 66% of present	decrease in baseflow component results in increased variance	larger number of low flow days may increase skew	decrease in baseflow resulting in decrease in persistence	rapid change and low flow periods would cause local shortages	dec. in ave. annual flow of 35%;not great enough to cause supply pblms; poll. inc. -3
Δ YIELD FROM RESERVOIRS	significant decrease because of increased low flow days	adversely affected by increased variance in streamflow-storage inadequate	storage inadequate because of extended low flow periods	decrease in persistence; storage inadequate	rapid change and low flow periods would cause local shortages	yield from reserv. greatly affected by insufficient storage -3
Δ YIELD FROM GROUND WATER SOURCES	decrease in streamflow decrease in recharge increase in demand on g.w. reservoirs	increase in variance of streamflow,more water fm. storage as baseflow less water available for wells	greater low flow days resulting in g.w. depletion through baseflow	decrease in surface water supply results in greater baseflow component & reduction of g.w. storage	large baseflow component would tend to suppress rapid changes	shallow aquifers & large baseflow components makes sensitivity high -4
Δ QUALITY OF UNTREATED WATER	decrease in baseflow causes increase in thermal and industrial water pollution	greater variance will cause increase in pollution	greater number of low flow days will increase pollution, cause salt water encroachment	decrease in persistence will tend to increase pollution & salt water encroachment	long duration of low flow would cause extreme deterioration of water quality	very great deterioration -4
EFFECTIVENESS OF INTERBASIN AND INTERSYSTEM CONNECTIONS	decrease in streamflow could make many systems inoperative	lack of storage and increase variation in streamflow would make present connections inadequate	greater skew may have some effect on connections	decrease in persistence will make greater need for interbasin diversions	long duration low flows would make for greater interbasin connections	because of magnitude of supply above projected demand, no great problem forseen -2
ESTIMATED SYSTEM RELIABILITY	overall system would be relaible because of large supply compared to demand	many urban systems would be unreliable during extended low flow periods	some change but probably not grossly affected	probably not adequate to handle decrease in storage	lack of storage could cause system unreliability	except locally, not greatly affected -2
MAGNITUDE AND CONTROL OF DEMAND	demand on system would increase & in many areas storage would prove inadequate	demand on system would increase because of the greater variation in flow	no effect	demand on system would be great at least locally	demand on system would be great	magnitude not great enough to cause great pblms. -2
COST OF OPERATION OF WATER SYSTEMS	cost would accelerate because of needed modifications	cost would increase	greater costs as modifications may be necessary	greater because of need to increase storage	cost would be excessive as short term modifications were made	costs could be great primarily because of lack of storage -3
ABILITY OF THE WATER SYSTEM TO RESPOND TO CLIMATIC VARIATION	system would be adversely affected but reasonable modifications would rectify the problem	many local systems would have inadequate storage	probably not great enough to cause large scale inadequacy	present storage would probably not be large enough	system would not be able to cope with extended low flow periods	overall not major -2

Appendix Table 4. Region 02, Scenario 2 (Cooler and Wetter)

	INCREASE (DECREASE) IN MEAN ANNUAL STREAMFLOW	INCREASE (DECREASE) IN VARIANCE OF STREAMFLOW	INCREASE(DECREASE) SKEWNESS OF DISTRIBUTION OF STREAMFLOW	INCREASE (DECREASE) IN PERSISTENCE OF STREAMFLOW	RAPIDITY & DURATION OF CHANGE IN STREAMFLOW	OVERALL REGIONAL SENSITIVITY TO CLIMATIC VARIATION
Δ YIELD FROM UNREGULATED BASINS	greatly increased	probably little change in variance	no change	greater persistence resulting from more baseflow may increase yield	little if any change	increased by about 1.4 times over present +1
Δ YIELD FROM RESERVOIRS	improved with flood control being a problem	no effect	no change	increased persistence may make flood storage inadequate	rapid changes and extended high flows would cause lack of flood storage	unlimited; flood storage may be inadequate -1
Δ YIELD FROM GROUND WATER SOURCES	increased	increase in baseflow component will tend to make flow more persistent	no change	baseflow component increased	not changed	unlimited +2
Δ QUALITY OF UNTREATED WATER	improved with greater flow	improved	no change	improved	not changed	not a problem +2
EFFECTIVENESS OF INTERBASIN AND INTERSYSTEM CONNECTIONS	no effect	no effect	no change	no effect	not changed	no effect +2
ESTIMATED SYSTEM RELIABILITY	may not be adequate for flood control	no effect	no change	increased persistence may make present flood protection inadequate	flood protection may be unreliable	good; except for possible flood control -1
MAGNITUDE AND CONTROL OF DEMAND	no effect	no effect	no change	no effect	not changed	no effect 0
COST OF OPERATION OF WATER SYSTEMS	increased as flood damages result	no effect	no change	increased as flood damages increase	increased for long duration high flows	increased by need for flood protection -3
ABILITY OF THE WATER SYSTEM TO RESPOND TO CLIMATIC VARIATION	inadequate flood storage may result	no change	no change	good except flood protection	good except for lack of flood storage	not a major regional problem +2

Appendix Table 5. Region 03, Scenario 1 (Warmer and Drier)

	INCREASE (DECREASE) IN MEAN ANNUAL STREAMFLOW	INCREASE (DECREASE) IN VARIANCE OF STREAMFLOW	INCREASE(DECREASE) SKEWNESS OF DISTRIBUTION OF STREAMFLOW	INCREASE (DECREASE) IN PERSISTENCE OF STREAMFLOW	RAPIDITY & DURATION OF CHANGE IN STREAMFLOW	OVERALL REGIONAL SENSITIVITY TO CLIMATIC VARIATION
Δ YIELD FROM UNREGULATED BASINS	decrease in present mean annual flow by .65 times	little change from present	little change from present	little change from present	little change from present	reduction in mean annual flow by .65 times present flow -2
Δ YIELD FROM RESERVOIRS	decreased as mean annual flow decreases	little change from present	little change from present	little change from present	little change from present	decrease as mean annual flow decreases; some small reservoirs suffer large declines -2
Δ YIELD FROM GROUND WATER SOURCES	little change from present	little change from present	little change from present	little change from present	little change from present	little change from present 0
Δ QUALITY OF UNTREATED WATER	little change from present	little change from present	little change from present	little change from present	little change from present	little change from present 0
EFFECTIVENESS OF INTERBASIN AND INTERSYSTEM CONNECTIONS	little change from present	little change from present	little change from present	little change from present	little change from present	little change from present 0
ESTIMATED SYSTEM RELIABILITY	little change from present	little change from present	little change from present	little change from present	little change from present	little change from present 0
MAGNITUDE AND CONTROL OF DEMAND	little change from present	little change from present	little change from present	little change from present	little change from present	little change from present 0
COST OF OPERATION OF WATER SYSTEMS	little change from present	little change from present	little change from present	little change from present	little change from present	little change from present 0
ABILITY OF THE WATER SYSTEM TO RESPOND TO CLIMATIC VARIATION	excellent; present and projected use well within reduction in flow	little change from present	little change from present	little change from present	little change from present	regional ability to respond is excellent; local shortages may occur; salt water encroachment may be major -2

Appendix Table 6. Region 03, Scenario 2 (Cooler and Wetter)

	INCREASE (DECREASE) IN MEAN ANNUAL STREAMFLOW	INCREASE (DECREASE) IN VARIANCE OF STREAMFLOW	INCREASE(DECREASE) SKEWNESS OF DISTRIBUTION OF STREAMFLOW	INCREASE (DECREASE) IN PERSISTENCE OF STREAMFLOW	RAPIDITY & DURATION OF CHANGE IN STREAMFLOW	OVERALL REGIONAL SENSITIVITY TO CLIMATIC VARIATION
Δ YIELD FROM UNREGULATED BASINS	increase in mean annual runoff by 1.7 times present runoff	little change from present	little change from present	little change from present	little change from present	increase in mean annual runoff by 1.7 times present runoff +1
Δ YIELD FROM RESERVOIRS	increased; flood storage may be inadequate	little change from present	little change from present	little change from present	little change from present	reservoir yield increased; flood storage capacity may be inadequate -2
Δ YIELD FROM GROUND WATER SOURCES	little change from present	little change from present	little change from present	little change from present	little change from present	little change from present -0
Δ QUALITY OF UNTREATED WATER	little change from present	little change from present	little change from present	little change from present	little change from present	little change from present 0
EFFECTIVENESS OF INTERBASIN AND INTERSYSTEM CONNECTIONS	little change from present	little change from present	little change from present	little change from present	little change from present	little change from present 0
ESTIMATED SYSTEM RELIABILITY	excellent; additional flood control may be necessary	little change from present	little change from present	little change from present	little change from present	excellent; additional flood control may be necessary -2
MAGNITUDE AND CONTROL OF DEMAND	little change from present	little change from present	little change from present	little change from present	little change from present	little change from present 0
COST OF OPERATION OF WATER SYSTEMS	slight increase if additional flood control is needed	little change from present	little change from present	little change from present	little change from present	some additional flood control may be needed -1
ABILITY OF THE WATER SYSTEM TO RESPOND TO CLIMATIC VARIATION	excellent; flooding may be a problem	little change from present	little change from present	little change from present	little change from present	response is slightly negative as additional flood control may be needed -1

Appendix Table 7. Region 04, Scenario 1 (Warmer and Drier)

	INCREASE (DECREASE) IN MEAN ANNUAL STREAMFLOW	INCREASE (DECREASE) IN VARIANCE OF STREAMFLOW	INCREASE(DECREASE) SKEWNESS OF DISTRIBUTION OF STREAMFLOW	INCREASE (DECREASE) IN PERSISTENCE OF STREAMFLOW	RAPIDITY & DURATION OF CHANGE IN STREAMFLOW	OVERALL REGIONAL SENSITIVITY TO CLIMATIC VARIATION
Δ YIELD FROM UNREGULATED BASINS	estimate decrease of 33% in mean annual runoff	increase in variation as baseflow component diminishes	skewness increases as low flow days increase	decrease in persistence as baseflow diminishes; low flow duration may increase	changes may be rapid because of increase in variation & duration of low flow periods extended	most basin yield will decrease but other sources available -2
Δ YIELD FROM RESERVOIRS	decrease; lake levels recession, increase in number of low flow days might cause local shortages	decrease as duration of low flows increase	decreases as skew increases	long periods of low flow may be problem	storage may be inadequate to handle rapid changes and low flow	reservoir storage probably too small -2
Δ YIELD FROM GROUND WATER SOURCES	notable decrease in shallow aquifers because of the surface water; deeper aquifers pumped more than present	decreases as recharge decreases	decrease in shallow aquifer	ground water levels decrease; baseflow contribution diminishing	may be affected by long duration of low flow	decrease in shallow aquifers; deep aquifers not effected -3
Δ QUALITY OF UNTREATED WATER	low flows resulting in industrial,urban & thermal waste disposal pblms. water quality deterioration	decreases as baseflow component decreases	decreases as pollution increases with low flow	poor especially in long duration low flow periods	poor as duration of low flow periods become more extensive	regional deterioration in quality; lake water quality also deteriorating -3
EFFECTIVENESS OF INTERBASIN AND INTERSYSTEM CONNECTIONS	probably not sufficient to handle local water shortages	increase in variation may make some connections inadequate	storage shortage may cause problems	decrease in effectiveness as persistence decreases	probably not sufficient to handle rapid changes and long duration of low flows	probably not effective, modifications necessary -3
ESTIMATED SYSTEM RELIABILITY	reliability good except in local conditions	storage probably small	present system may need expansion	may be unreliable in long duration low flow periods	storage inadequate but changes found use of lake and ground water feasible	unreliable but minor changes could make it reliable -2
MAGNITUDE AND CONTROL OF DEMAND	magnitude of demand increasing with lake water available for control	magnitude of demand fluctuates with variability; control may be possible from lake water or deep aquifers	magnitude of demand increases with control by conjunctive use of lake and ground water	magnitude of demand increases during extended low flow periods	large magnitude in demand as precipitation decreases & evaporation increases	overall magnitude great because of large urban need-control by conj. -3 use of lake and g.w
COST OF OPERATION OF WATER SYSTEMS	increasing to accomodate local problems	increased as system is taxed	increased as modifications become necessary	increases as need for expansion increases	increases as modifications become necessary	increased as need for changes become necessary -3
ABILITY OF THE WATER SYSTEM TO RESPOND TO CLIMATIC VARIATION	good except locally	good; as conjunctive use measures are readily feasible	other sources are readily available for use; water pollution may be greatest pblm.	probably not good as baseflow persistence is essential for system operations	modifications in storage necessary	overall some changes necessary but other sources are available -2

Appendix Table 8. Region 04, Scenario 2 (Cooler and Wetter)

	INCREASE (DECREASE) IN MEAN ANNUAL STREAMFLOW	INCREASE (DECREASE) IN VARIANCE OF STREAMFLOW	INCREASE(DECREASE) SKEWNESS OF DISTRIBUTION OF STREAMFLOW	INCREASE (DECREASE) IN PERSISTENCE OF STREAMFLOW	RAPIDITY & DURATION OF CHANGE IN STREAMFLOW	OVERALL REGIONAL SENSITIVITY TO CLIMATIC VARIATION
Δ YIELD FROM UNREGULATED BASINS	estimated increase in annual runoff of 1.37 times	decreases as baseflow becomes dominant over whole basin	decreases in skewness as baseflow increases	increases as baseflow becomes predominant	unlimited	decrease in variation and increase in baseflow +2
Δ YIELD FROM RESERVOIRS	increased to maximum, flood control may be problem	improved to unlimiting	unlimited	unlimited	rapid change in high flows causes inadequate flood protection	unlimited except for flood protection +2
Δ YIELD FROM GROUND WATER SOURCES	unlimited	unlimited	unlimited	unlimited	unlimited	unlimited +2
Δ QUALITY OF UNTREATED WATER	good as increase in flow removes wastes	improved as baseflow increases	improved as baseflow increases	improved as baseflow increases	excellent	excellent as baseflow increases, improves quality region wide +3
EFFECTIVENESS OF INTERBASIN AND INTERSYSTEM CONNECTIONS	no effect	no effect	no effect	no effect	no effect	no effect 0
ESTIMATED SYSTEM RELIABILITY	no effect except for flood control	no effect	no effect	flood control storage may be inadequate	no effect	flood control may be inadequate -1
MAGNITUDE AND CONTROL OF DEMAND	demand decreases	no effect	no effect	no effect	no effect	no effect 0
COST OF OPERATION OF WATER SYSTEMS	slight increase for flood control	no effect	increase in high flow may cause increase in flooding	increased of flood control measures are needed	no effect	increased flood control will raise costs -1
ABILITY OF THE WATER SYSTEM TO RESPOND TO CLIMATIC VARIATION	good except in low areas and in flood plains	good; equal to present except if lake levels rise to catastrophic highs	good with drainage being an unknown factor	good; flood control improvement may be needed	flood protection may be inadequate for rapid high flow changes	some pblms, if lake levels rise drastically but overall response effect positive +2

Appendix Table 9. Region 05, Scenario 1 (Warmer and Drier)

	INCREASE (DECREASE) IN MEAN ANNUAL STREAMFLOW	INCREASE (DECREASE) IN VARIANCE OF STREAMFLOW	INCREASE(DECREASE) SKEWNESS OF DISTRIBUTION OF STREAMFLOW	INCREASE (DECREASE) IN PERSISTENCE OF STREAMFLOW	RAPIDITY & DURATION OF CHANGE IN STREAMFLOW	OVERALL REGIONAL SENSITIVITY TO CLIMATIC VARIATION
Δ YIELD FROM UNREGULATED BASINS	decrease of 38%	increase in variation with decrease in baseflow	skew increases as larger number of low flow days increase	decrease as baseflow is less. Low flow may be more persistent	duration of low flows increase - rapid change in smaller basins	flow from most basins is more variable -2
Δ YIELD FROM RESERVOIRS	decrease; baseflow component is less	larger fluctuations, less yield, total storage may be inadequate	lower yield; larger number of low flow days	storage may be inadequate	not adequate for long period low flows	reservoir capacity may not be large enough to handle low flows -2
Δ YIELD FROM GROUND WATER SOURCES	falling water levels shallow aquifers adversely affected by decreased streamflow	less yield as shallow aquifers recharge is affected by reduced streamflow	decrease in recharge	less as storage decreases	decreases as length of low flows increase	shallow aquifers will be depleted -2
Δ QUALITY OF UNTREATED WATER	low flow causes increase in pollution	less baseflow results in increase pollution	deterioration as low flow days increase	poor unless industrial and thermal wastes are controlled	poor if waste is not controlled	general decline in quality of region -2
EFFECTIVENESS OF INTERBASIN AND INTERSYSTEM CONNECTIONS	may not be adequate to handle local needs	may not be designed to handle fluctuations	may not be capable of handling extended low flow periods	non-effective if low flow days are great	may be inadequate to handle extended low flows	probably ineffective for long duration low flows -2
ESTIMATED SYSTEM RELIABILITY	overall reliable; locally may need modification	overall reliable; some local navigation pblms. from low water	reliable; local modifications necessary	minor modifications necessary	longer low flow periods may require increased storage	modification necessary, storage increase, treatment increase -2
MAGNITUDE AND CONTROL OF DEMAND	demand increases with lowering g.w. levels, reservoirs may furnish adequate control	demand increases as baseflow decreases	increased water use controlled by restriction	increase in demand with long duration low flows	demand increase controlled by restriction	demand increased conjunctive use with deeper g.w. possible control -2
COST OF OPERATION OF WATER SYSTEMS	cost increases as modifications are necessary	cost increases as remedial measures become necessary	increased due to necessary modifications	increased as modifications are needed to increase storage etc.	increases; need for modification including increase treatment & storage	cost increases with modifications -2
ABILITY OF THE WATER SYSTEM TO RESPOND TO CLIMATIC VARIATION	overall supply is adequate; local shortages and pollution may be problems	increase variation in streamflow may present local problems because of lack of storage	modification necessary but supply is adequate	fair - inadequate storage and pollution are major problems	probably not able to handle long duration low flows	supply adequate except in long duration low flows -2

Appendix Table 10. Region 05, Scenario 2 (Cooler and Wetter)

	INCREASE (DECREASE) IN MEAN ANNUAL STREAMFLOW	INCREASE (DECREASE) IN VARIANCE OF STREAMFLOW	INCREASE(DECREASE) SKEWNESS OF DISTRIBUTION OF STREAMFLOW	INCREASE (DECREASE) IN PERSISTENCE OF STREAMFLOW	RAPIDITY & DURATION OF CHANGE IN STREAMFLOW	OVERALL REGIONAL SENSITIVITY TO CLIMATIC VARIATION
Δ YIELD FROM UNREGULATED BASINS	increase of 1.43 times present	greater baseflow may decrease variance in some arbitrary basins	decrease in skewness as baseflow increases	increase in overall persistence with greater baseflow	larger high flows little change in rapidity	greater, less variable, more persistent mean annual flows +2
Δ YIELD FROM RESERVOIRS	probably unlimited flow may not be adequate	increased as baseflow increases	increased for given amount of storage	increased with higher annual mean flow and persistence	increased with longer high flows	increased to near capacity +2
Δ YIELD FROM GROUND WATER SOURCES	increases	not affected	not affected	increased as reflected in increased baseflow	unlimited	improved; drainage may be problem +2
Δ QUALITY OF UNTREATED WATER	good, except in areas poor drainage	good, greater baseflow tends to remove wastes better	improved with higher baseflow	improved with higher baseflow	good as high flows remove wastes	excellent, high baseflows effective in removing wastes +1
EFFECTIVENESS OF INTERBASIN AND INTERSYSTEM CONNECTIONS	not affected	not affected	not affected	not affected	not affected	not affected 0
ESTIMATED SYSTEM RELIABILITY	highly relaible except for flood control	high	flood storage may be inadequate	drainage and flooding protection may be unreliable	good; flood protection may be inadequate	good; flooding and drainage pblms. +2
MAGNITUDE AND CONTROL OF DEMAND	not affected	not affected	not affected	not affected	not affected	not affected 0
COST OF OPERATION OF WATER SYSTEMS	increased if flood control measures are necessary	some drainage problems may raise costs	flood control measures may increase costs	some increase for drainage improvements	some rise for improved flood control	some rise to handle flood and drainage problem -1
ABILITY OF THE WATER SYSTEM TO RESPOND TO CLIMATIC VARIATION	excellent; local flood control necessary	excellent; measures to improve drainage may be necessary	good; flood control may be necessary	good; drainage improvements necessary	good; flood control may be inadequate	good; flood control & drainage may be inadequate +3

Appendix Table 11. Region 06, Scenario 1 (Warmer and Drier)

	INCREASE (DECREASE) IN MEAN ANNUAL STREAMFLOW	INCREASE (DECREASE) IN VARIANCE OF STREAMFLOW	INCREASE (DECREASE) SKEWNESS OF DISTRIBUTION OF STREAMFLOW	INCREASE (DECREASE) IN PERSISTENCE OF STREAMFLOW	RAPIDITY & DURATION OF CHANGE IN STREAMFLOW	OVERALL REGIONAL SENSITIVITY TO CLIMATIC VARIATION
Δ YIELD FROM UNREGULATED BASINS	reduction to 63 percent of present mean annual flow	increase in variance	increase in skewness with decrease in baseflow	decrease in baseflow results in decrease in persistence; increase in low flow persistence	fast changes and long duration low flows	decrease by significant amount; baseflow less -3
Δ YIELD FROM RESERVOIRS	reduced as mean annual flow is reduced; storage may be inadequate	decrease as storage may not adequately handle increase in variation	decrease as number of low flow days increase	decreased as persistence decreases and low flow periods increase	inadequate storage for extended low flows	decrease as mean, persistence both decrease -2
Δ YIELD FROM GROUND WATER SOURCES	reduced because of reduction in runoff	decrease because of longer low flow periods	decrease as recharge decreases	shallow aquifers decrease as persistence decreases	decrease from shallow aquifers	decrease, especially in shallow aquifers tied to surface water -3
Δ QUALITY OF UNTREATED WATER	deteriorated because of low flows and reduced base flow	poor as low flows increase	deteriorates as low flow predominates	poor as low flows predominate	poor during long low flow periods	deterioration, unless dumping of wastes is curtailed -3
EFFECTIVENESS OF INTERBASIN AND INTERSYSTEM CONNECTIONS	locally may be ineffective; conjunctive use of surface and ground water may be necessary	probably not able to handle increase in variation	ineffective during extended low flow periods	ineffective especially during extended low flow periods	ineffective as duration of low flows is extended	ineffective as mean decreases and baseflow decreases -3
ESTIMATED SYSTEM RELIABILITY	good- local shortages, poll. & navig. pblms. Fish & wildlife may be adversely effected	fair- pblms. in inadequate storage, pollution, fish and wildlife	fair- local water shortage, pollution, navigation pblms.	fair- storage capacity may be inadequate	poor- long duration low flows, shortages, navig. , poll., fish-wildlife pblms.	fair to poor- shortages, poll., fish-wildlife, navig. major pblms. -3
MAGNITUDE AND CONTROL OF DEMAND	demand increase as result of charge; conjunctive use of g.w. for control	demand increasing, g.w. used conjunctively to control demand	demand increasing more use of g.w.	demand increases for agricultural-urban users; controlled by g.w. (deeper aquifers)	large demand increase, control by use of g.w.	increase demand deep g.w. used locally to control demands -2
COST OF OPERATION OF WATER SYSTEMS	increased as modification becomes necessary	increased as modifications needed	increased to correct problems	increased as modifications necessary	increased, need for modification	general increase as modifications are necessary -2
ABILITY OF THE WATER SYSTEM TO RESPOND TO CLIMATIC VARIATION	good; fish&wildlife, local winter supplies, poll., navig. pblms.	fair; long low flows cause shortages, poll., fish&wildlife, navig. pblms.	fair; fish wildlife, navig. pblms., shortages predominate	poor; storage, navig., fish&wildlife, pollution all problems	poor for long duration low flows	region adversely effected- water system needs modifications to be effective -3

Appendix Table 12. Region 06, Scenario 2 (Cooler and Wetter)

	INCREASE (DECREASE) IN MEAN ANNUAL STREAMFLOW	INCREASE (DECREASE) IN VARIANCE OF STREAMFLOW	INCREASE (DECREASE) SKEWNESS OF DISTRIBUTION OF STREAMFLOW	INCREASE (DECREASE) IN PERSISTENCE OF STREAMFLOW	RAPIDITY & DURATION OF CHANGE IN STREAMFLOW	OVERALL REGIONAL SENSITIVITY TO CLIMATIC VARIATION
Δ YIELD FROM UNREGULATED BASINS	increase by 1.38 times over present	decreases as baseflow increases	decrease in skewness but little change from present	increase in persistence as baseflow is greater	increased duration of water flows	increased mean annual flow; water baseflow +3
Δ YIELD FROM RESERVOIRS	increased to maximum	increased as mean annual runoff increases	increased as baseflow increases	increased to near maximum capacity	increased to near maximum; flood storage may be inadequate	all reserv. yields increased; addit. flood storage may be necessary +2
Δ YIELD FROM GROUND WATER SOURCES	increased to near maximum	increases as recharge increases	increased as low flow is less	increased as water levels rise	long duration of high flows results in max. recharge to shallow aquifers	available yields increased to near max. +3
Δ QUALITY OF UNTREATED WATER	improved as higher flows remove wastes	improved as level of waste injection remains constant	improved as low flow is less	excellent as baseflow removes waste products more readily	excellent; high flows flush system regularly	quality improved if level of waste injected remains same +3
EFFECTIVENESS OF INTERBASIN AND INTERSYSTEM CONNECTIONS	no effect	no effect	no effect	no effect	no effect	no effect 0
ESTIMATED SYSTEM RELIABILITY	good except flood storage may be inadequate	good; some flood control improvements & drainage pblms. in valleys	good; some drainage problems in low areas	good; storage may need to be increased	good; flood storage capacity may be inadequate. Drainage in low lands inadequate	good; some changes needed in flood control, drainage in low areas +2
MAGNITUDE AND CONTROL OF DEMAND	no effect	no effect	no effect	nc effect	no effect	no effect 0
COST OF OPERATION OF WATER SYSTEMS	increased if flood control is increased	increased as modifications needed	some increase as modifications needed	increased as modifications are needed	increased as flood control modifications are needed	good; some additional flood control need & drainage improvement +2
ABILITY OF THE WATER SYSTEM TO RESPOND TO CLIMATIC VARIATION	good; some changes necessary in flood control	good; flood control may be inadequate	good; drainage pblms. require some changes	good; some increase in storage capacity needed	good; long high flows may require channel improvements; flood control; drainage improvements	good; flooding and drainage major problem areas +3

Appendix Table 13. Region 07, Scenario 1 (Warmer and Drier)

	INCREASE (DECREASE) IN MEAN ANNUAL STREAMFLOW	INCREASE (DECREASE) IN VARIANCE OF STREAMFLOW	INCREASE(DECREASE) SKEWNESS OF DISTRIBUTION OF STREAMFLOW	INCREASE (DECREASE) IN PERSISTENCE OF STREAMFLOW	RAPIDITY & DURATION OF CHANGE IN STREAMFLOW	OVERALL REGIONAL SENSITIVITY TO CLIMATIC VARIATION
Δ YIELD FROM UNREGULATED BASINS	decrease of 38 % from present	increase in variance as baseflow contribution declines	increase in skewness as low flow predominates, may be significant	decrease in overall persistence as baseflow declines; low flow days may increase	long duration of low flows may result in extended periods of inadequate flow	about 40% less yield; duration of low flows may increase -3
Δ YIELD FROM RESERVOIRS	decrease proportional to decrease in flow	decrease as storage may not be adequate to handle change in variance	decrease as skew increases if significant	decrease in yield - smaller reservoirs more affected	decrease if duration of low flow increase; Small reservoirs most severely affected	most yields decline with small reservoirs most severely affected -2
Δ YIELD FROM GROUND WATER SOURCES	decrease as recharge decreases; usage may increase greatly for agricultural purposes	decrease as recharge declines	decrease as low flow implies decrease in recharge	decline as recharge declines; usage may increase causing further decline	longer low flow periods result in less recharge	shallow aquifers may be severely effected; deep aquifers used more heavily -2
Δ QUALITY OF UNTREATED WATER	deteriorates as low flow becomes more prevalent	deteriorates as low flow becomes more common	becomes poorer and low flow predominates	deteriorates as low flow predominates	lengthy low flow periods cause severe local deterioration	general deterioration if present level of pollution increases -3
EFFECTIVENESS OF INTERBASIN AND INTERSYSTEM CONNECTIONS	less effective as flows diminish	less effective especially during low flows	less effective; storage navigation, pollution problem areas	less baseflow may have some effects on some systems	larger low flows may cause need for increased storage	some connections ineffective -2
ESTIMATED SYSTEM RELIABILITY	good except for poll.& fish-wildlife requirements. Stress may come from agricultural usage	good; storage inadequate, pollution increases, some navigation difficulties	good; increase needed in storage	decrease in persistence makes parts of the system unreliable	duration of low flows increasing causes loss in reliability	system generally reliable; needs -2 increase in storage pollution control, navig. improvements
MAGNITUDE AND CONTROL OF DEMAND	large increase in demand primarily from ag. control by conjunctive use of g.w.	increase in demand, storage may be increased, g.w. used more effectively	increase in demand as ag. comes under stress	increase in demand as persistence decreases	long duration low flows cause increased demand	demand increases region wide; conjunctive use of g.w. used as control -3
COST OF OPERATION OF WATER SYSTEMS	same increase if stress comes from ag.	increased as modifications to present system increase	increased as modifications required	increased costs as demand increases	increased costs as low flow predominates	cost increased as modifications needed -2
ABILITY OF THE WATER SYSTEM TO RESPOND TO CLIMATIC VARIATION	good; supply seems adequate, some local problems; ag. may turn more toward irrigation	good; storage may not be large enough; navig. may suffer; poll. increase; local water shortages for urban &ag	good; fish-wildlife may be improved; ag. needs increase; local water shortages	decrease in persistence causes need for more storage, poll. control, navig. improvements, increase in use of g.w.	long duration low flow makes changes in present system necessary	need for changes region wide; g.w. -3 development, storage imprv., navig. imprv., poll. imprv

Appendix Table 14. Region 07, Scenario 2 (Cooler and Wetter)

	INCREASE (DECREASE) IN MEAN ANNUAL STREAMFLOW	INCREASE (DECREASE) IN VARIANCE OF STREAMFLOW	INCREASE(DECREASE) SKEWNESS OF DISTRIBUTION OF STREAMFLOW	INCREASE (DECREASE) IN PERSISTENCE OF STREAMFLOW	RAPIDITY & DURATION OF CHANGE IN STREAMFLOW	OVERALL REGIONAL SENSITIVITY TO CLIMATIC VARIATION
Δ YIELD FROM UNREGULATED BASINS	increase in yield; 1.5 times present mean annual flow	decrease as baseflow increases	decrease; fewer low flow days	increase in persistence as baseflow is greater and of longer duration	duration of high flows and baseflows increased	increase in yield of about 1.5 times longer duration of high flows, baseflow increases in magnitude & duration +2
Δ YIELD FROM RESERVOIRS	increased; may make flood storage capacity inadequate	increased with decrease in variance and higher mean flow	increased as low flows decrease	increased; smaller reservoirs may be full most of the time	increased as high flow duration increased	all reservoirs increased in yield; smaller reserv. may have inadequate storage +2
Δ YIELD FROM GROUND WATER SOURCES	increased as recharge is more	increased; little or no fluctuations in water level of shallow aquifers, dec. in pumping	increased to maximum water level	increased to near maximum; water level high so some drainage problems	high flows tend to increase recharge to near maximum	shallow aquifers highly saturated; deep aquifers not greatly affected +2
Δ QUALITY OF UNTREATED WATER	improved as high flows flush system	inproved with higher baseflow	important as higher baseflow allows "flushing" of system	improved as baseflow is increased	high flows tend to improve quality	greater baseflow & longer duration of high flows improve greatly +3
EFFECTIVENESS OF INTERBASIN AND INTERSYSTEM CONNECTIONS	no effect	no effect	no effect	no effect	no effect	no effect 0
ESTIMATED SYSTEM RELIABILITY	good; flood storage capacity may be low; some channel imprv. nec., low land drainage is problem	good; normal reservoir capacity at max.; flood storage may be inadeq. ice flows may be pblm.	little or no change over present	good; ice flows may be pblm.; flood storage short; channelization may be necessary	good; longer duration high flows could cause flood storage problems	good; some channelization, flood storage & drainage improvements needed +2
MAGNITUDE AND CONTROL OF DEMAND	no effect	no effect	no effect	no effect	no effect	no effect 0
COST OF OPERATION OF WATER SYSTEMS	increased if flood protection increased	increased if modifications necessary	little or no change over present	some increase as modification needed	some increase if modifications are necessary for flood control	general increase in costs as some modifications are necessary -2
ABILITY OF THE WATER SYSTEM TO RESPOND TO CLIMATIC VARIATION	generally good; some navigation problems; ice flows, flooding	good; flood storage, drainage channel improvement may be necessary	good; little change from present	good; channelization, increase flood storage; ice flow flooding are all problems	increase needed in flood control, drainage channelization	overall system should be capable of handling this change (with some modification) +2

Appendix Table 15. Region 08, Scenario 1 (Warmer and Drier)

	INCREASE (DECREASE) IN MEAN ANNUAL STREAMFLOW	INCREASE (DECREASE) IN VARIANCE OF STREAMFLOW	INCREASE(DECREASE) SKEWNESS OF DISTRIBUTION OF STREAMFLOW	INCREASE (DECREASE) IN PERSISTENCE OF STREAMFLOW	RAPIDITY & DURATION OF CHANGE IN STREAMFLOW	OVERALL REGIONAL SENSITIVITY TO CLIMATIC VARIATION
Δ YIELD FROM UNREGULATED BASINS	decrease of 30 percent from present	increase in variance decreases yield- baseflow less	increase in skewness as low flows predominate; baseflow falls	decrease in persistence as baseflow decreases; increase in low flow persistence	duration of low flows increase	decline of yield; more variable flow, greater numbers of low flow -1
Δ YIELD FROM RESERVOIRS	decrease; smaller reservoirs on upper tributaries most affected	decrease as low flows increase	decrease as low flows predominate	decrease as persistence decreases	low flow duration may make many small reservoirs inadequate	yield from reservoirs decrease as mean flow decreases variance inc. & persistence decr. -1
Δ YIELD FROM GROUND WATER SOURCES	probably little effect because of outside recharge sources & vastness	some decrease as baseflow decreases but probably not significant	decreases as recharge decreases; increased usage also causes water level decline	decreases as persistence decreases, recharge is less	long duration of low flow causes serious water level decline	ground water is so vast probably total effect is small -1
Δ QUALITY OF UNTREATED WATER	deteriorates with greater low flow of Mississippi River	deteriorates as low flows are more common	deteriorates as low flows predominate	decrease in persistence with greater number of low flows causes serious pollution	long duration of low flows causes serious pollution	general increase in low flows with great inflow (poll) causes serious pollution -2
EFFECTIVENESS OF INTERBASIN AND INTERSYSTEM CONNECTIONS	decrease as low flows increase	some loss in effectiveness as variance incr. may cause storage shortages	less effective than present; may be inadequate	less effective as persistence declines	longer duration of low flows causes inadequate supply	some shortages cause some ineffectiveness -1
ESTIMATED SYSTEM RELIABILITY	good; dependent on inflow fluctuation	good; storage may be inadequate; conjunctive use of ground water will help	good; major problem on Miss. for navigation; also pollution problems	decline as persistence declines	unreliable in long duration low flows	major effects on Miss. River & trib. to navigation; ag. water shortages -1
MAGNITUDE AND CONTROL OF DEMAND	demand increase with greater use of ground water especially for irrigation	increase in demand; larger storage and conjunctive use of ground water for control	increased especially by agriculture as drainage improves	increase demand as baseflow declines	great increase during long low flows	overall incr. in demand, ag. uses incr., ground water used extensively -1
COST OF OPERATION OF WATER SYSTEMS	increase if modifications necessary	increased because of needed modifications	some increase as modifications needed	increase as storage needs increase	increased as storage needs increase	modification needed to Miss. River channel; more surface storage; more wells -1
ABILITY OF THE WATER SYSTEM TO RESPOND TO CLIMATIC VARIATION	good; navig. pblms. on Miss. River & major trib.; poll. increase, local water shortages	good; low flows will necessitate improvements for navig.; local systems may be inadequate	good; storage may be may be inadequate; dredging increased; poll. more severe	good; navigation improvements needed; pollution control	system may be severely stressed in longer low flows	good: change in channel on Miss. incr. wells for ag. poll. incr. salt water encroach. -1

Appendix Table 16. Region 08, Scenario 2 (Cooler and Wetter)

	INCREASE (DECREASE) IN MEAN ANNUAL STREAMFLOW	INCREASE (DECREASE) IN VARIANCE OF STREAMFLOW	INCREASE (DECREASE) SKEWNESS OF DISTRIBUTION OF STREAMFLOW	INCREASE (DECREASE) IN PERSISTENCE OF STREAMFLOW	RAPIDITY & DURATION OF CHANGE IN STREAMFLOW	OVERALL REGIONAL SENSITIVITY TO CLIMATIC VARIATION
Δ YIELD FROM UNREGULATED BASINS	increase by 1.37 times above present	decrease in variance as baseflow increases	little change from present	some increase in persistence probably not much different than present	rapidity of change declines; higher baseflow	increase in yield; decrease in variation +2
Δ YIELD FROM RESERVOIRS	increased as $\bar{Q}$ mean is longer	increased as variance is decreased	little change	increase in persistence as baseflow increases	little change	increased yield from reservoirs; flood storage inadequate +2
Δ YIELD FROM GROUND WATER SOURCES	increased as recharge increases	decrease in variance causes more recharge	little change	increase in persistence from upstream increases in recharge	little change	yields from g.w. increases to near maximum; drainage becomes pblm. +2
Δ QUALITY OF UNTREATED WATER	improved as flow increases; increased poor drainage may cause local pblms.	little change	little change	increase in persistence allow more efficient waste removal	little change	water quality improves over all of region except in areas where drain. is pblm. +3
EFFECTIVENESS OF INTERBASIN AND INTERSYSTEM CONNECTIONS	probably little effect	little change	little change	little change	little change	little change for present 0
ESTIMATED SYSTEM RELIABILITY	flood protection inadequate, low lands flooded; poor drainage	little change	little change	increase in persistence causes increased drainage problems	longer duration high flows creates excess of water	flooding and increased drainage problems for low lands -3
MAGNITUDE AND CONTROL OF DEMAND	no change	no change	no change	no change	no change	no change 0
COST OF OPERATION OF WATER SYSTEMS	increased as flood control pblms. mount; drainage improvement necessary	little change	little change	cost increased as higher flows help navig. but causes flood & drainage problems	longer high flows make present system flor flood and drainage	major rise in cost due to flood control improvements; drainage imprvmts. -4
ABILITY OF THE WATER SYSTEM TO RESPOND TO CLIMATIC VARIATION	poor to fair as region already has excess of water	little change	little change	greater persistence of high flow help navigation but causes flood & drainage problems	longer high flows make present system inadequate for flood and drainage	reg. has excess now inc. of mean flow & higher persistence causes flooding of low lands -4

Appendix Table 17. Region 09, Scenario 1 (Warmer and Drier)

	INCREASE (DECREASE) IN MEAN ANNUAL STREAMFLOW	INCREASE (DECREASE) IN VARIANCE OF STREAMFLOW	INCREASE(DECREASE) SKEWNESS OF DISTRIBUTION OF STREAMFLOW	INCREASE (DECREASE) IN PERSISTENCE OF STREAMFLOW	RAPIDITY & DURATION OF CHANGE IN STREAMFLOW	OVERALL REGIONAL SENSITIVITY TO CLIMATIC VARIATION
Δ YIELD FROM UNREGULATED BASINS	decrease by 45% from present	increase in variance as low flows become more dominant	increase in skewness as low flows increase	decrease in persistence	longer duration of low flows	decrease in mean by 45%, more variable, less persistent flow, longer duration of low flow -2
Δ YIELD FROM RESERVOIRS	decrease as $\bar{Q}$ decreases	decreases as variance increases	decreases as skew increases	decrease as persistence becomes less	decrease as low flow duration increases	reserv. yields decr. as $\bar{Q}$ decr, variance incr, skew incr., persist. rises & low flows longer -2
Δ YIELD FROM GROUND WATER SOURCES	decrease as recharge decreases	decreases as flows become less (especially shallow aquifers)	decreases as skew increases	decreases as flow becomes less persistent	decreases as low flow duration increases	ground water level decline, especially shallow aquifers; ag. use accelerates -3
Δ QUALITY OF UNTREATED WATER	little or no change	little or no change	little or no change	little or no change	little or no change	little or no change 0
EFFECTIVENESS OF INTERBASIN AND INTERSYSTEM CONNECTIONS	less effective with decline in $\bar{Q}$ and reservoir yield	little change	little change	decrease in persistence causes local water shortages	long duration of low flows cause shortage	connections (if any) are less effective 0
ESTIMATED SYSTEM RELIABILITY	good; little irrigation small population makes for little incr. in demand	little change	little change	little change	long duration low flows make local systems inadequate	good system reliability because of low use; increase in ground water production -1
MAGNITUDE AND CONTROL OF DEMAND	increase in magnitude of demand, more use of ground water	little change	little change	little change	longer low flows cause increase in ground water use	magnitude incr.; more use of ground water for irrig.; farm land abandoned -2
COST OF OPERATION OF WATER SYSTEMS	some increase but primarily to public utilities & individual farmers	little change	little change	little change	increase in costs as low flows increase causing turn to ground water	some incr. in costs mostly conversion to ground water by utilities & farmers -2
ABILITY OF THE WATER SYSTEM TO RESPOND TO CLIMATIC VARIATION	not much change as little use of surface water made : ground water should be able to make up losses	little change	little change	little change	some change to ground water as surface water low flows are longer	ag. hurt most; change to ground water; farm land abandoned if too severe -2

Appendix Table 18. Region 09, Scenario 2 (Cooler and Wetter)

	INCREASE (DECREASE) IN MEAN ANNUAL STREAMFLOW	INCREASE (DECREASE) IN VARIANCE OF STREAMFLOW	INCREASE(DECREASE) SKEWNESS OF DISTRIBUTION OF STREAMFLOW	INCREASE (DECREASE) IN PERSISTENCE OF STREAMFLOW	RAPIDITY & DURATION OF CHANGE IN STREAMFLOW	OVERALL REGIONAL SENSITIVITY TO CLIMATIC VARIATION
Δ YIELD FROM UNREGULATED BASINS	increase in $\bar{Q}$ to 1.68 times present	less variance	decrease in skew	some increase in persistence	longer high flows	increase in yield by 1.68, decr. in variation skw but higher persist. +2
Δ YIELD FROM RESERVOIRS	increase as $\bar{Q}$ increases	increased as variance decreases	increased as skew decreases	increases as persistence increases	increased as duration of high flows increase	increase in yield as $\bar{Q}$ incr. & vari. skew, decr. & persistence incr. +2
Δ YIELD FROM GROUND WATER SOURCES	increased as recharge more abundant	little change	little change	little change	little change	yield incr., use declines for ag. purposes +2
Δ QUALITY OF UNTREATED WATER	little change	little change	little change	little change	little change	little change as already good to excellent 0
EFFECTIVENESS OF INTERBASIN AND INTERSYSTEM CONNECTIONS	little change	little change	little change	little change	little change	little change 0
ESTIMATED SYSTEM RELIABILITY	good for supply poor for flood control	little change	little change	little change	little change	good for supply, poor for flood control; incr. ag. makes -1
MAGNITUDE AND CONTROL OF DEMAND	little change	little change	little change	little change	little change	little change 0
COST OF OPERATION OF WATER SYSTEMS	increase for flood control	little change	little change	little change	little change	increased cost for flood control -1
ABILITY OF THE WATER SYSTEM TO RESPOND TO CLIMATIC VARIATION	good; ag. use may increase unless temp becomes prohibitive; flooding major pblm.	little change	little change	little change	little change	good; lower temp. may hurt ag.; flooding problems increase +1

Appendix Table 19. Region 10, Scenario 1 (Warmer and Drier)

	INCREASE (DECREASE) IN MEAN ANNUAL STREAMFLOW	INCREASE (DECREASE) IN VARIANCE OF STREAMFLOW	INCREASE(DECREASE) SKEWNESS OF DISTRIBUTION OF STREAMFLOW	INCREASE (DECREASE) IN PERSISTENCE OF STREAMFLOW	RAPIDITY & DURATION OF CHANGE IN STREAMFLOW	OVERALL REGIONAL SENSITIVITY TO CLIMATIC VARIATION
Δ YIELD FROM UNREGULATED BASINS	decrease in $\bar{Q}$ annual by 65 percent	probable increase in variance as low flows are more common	increase in skewness as low flows prevail	decrease in persistence as baseflow declines	duration of low flows increase	65% decrease in $\bar{Q}$ annual flows more variable, more skewed, less persistent -4
Δ YIELD FROM RESERVOIRS	decrease as $\bar{Q}$ annual decreases	decreases as variance of inflows increase	decreases as skewness increases	decreases as persistence decreases; and as duration of low flows increase	decreases as duration of low flows increase	large decrease in reservoir yield -4
Δ YIELD FROM GROUND WATER SOURCES	decreases as $\bar{Q}$ mean decreases and ET increase	decreases as variance in flow increases	decreases as skew increases (longer low flow periods)	decreases as persistence decreases	decreases as duration of low flow increases	yield from g.w. decreases (espeially is shallow aquifers) -4
Δ QUALITY OF UNTREATED WATER	deterioration; but not major pblm. as waste disposal is not a region problem	deteriorates as variance increases	deteriorates as skewness increases	deteriorates as persistence decreases	deteriorates as duration of low flows increase	general deterioration in quality but not a major pblm. in this region -2
EFFECTIVENESS OF INTERBASIN AND INTERSYSTEM CONNECTIONS	more effective if result is more imported water	more effective if imported water used to decrease variance	more effective if used to import water from outside region	more effective	more effective especially during long duration low flows	more effective if imported water eases shortage +2
ESTIMATED SYSTEM RELIABILITY	fair; large decrease in runoff may make large storage ineffective	increase in variance may have adverse effect on reservoir storage	increase in skewness may result in insufficient input to storage	less persistence may cause storage inadequacies	longer duration low flows cause overall system ineffectiveness	fair to poor; in flows to storage inadequate; incre. demand by ag.,heavy use of g.w. -4
MAGNITUDE AND CONTROL OF DEMAND	large increase in water demand for ag.; ground water used when possible	increase in demand as variance is higher; surface storage inadequate	increase in demand as skewness increases; surface storage inadequate	increase in demand as surface storage may be inadequate	longer low flows make demand higher; shortages of surface water	large increase in demand for ag.; surface water storage short; g.v.used heavily (if avail.) -4
COST OF OPERATION OF WATER SYSTEMS	increased as modifications are necessary; g.w. production costs increased as water level declines	increases as variance increases	increased as skewness increases	increased as persistence decreases	increased as low flows predominate	large increases as changes are made to handle increased demand -4
ABILITY OF THE WATER SYSTEM TO RESPOND TO CLIMATIC VARIATION	probably not good as $\bar{Q}$ is drastically reduced; surface water shortages, navig. pblm more g.w. use for ag.	probably poor as surface storage may be adversely affected	poor; surface storage may be ineffective	poor; surface water storage adversly affected	poor; long duration low flows effect storage and navigation	system response bad; shortage of surface water for ag. & navig.,g.w. used heavily -4

Appendix Table 20. Region 10, Scenario 2 (Cooler and Wetter)

	INCREASE (DECREASE) IN MEAN ANNUAL STREAMFLOW	INCREASE (DECREASE) IN VARIANCE OF STREAMFLOW	INCREASE(DECREASE) SKEWNESS OF DISTRIBUTION OF STREAMFLOW	INCREASE (DECREASE) IN PERSISTENCE OF STREAMFLOW	RAPIDITY & DURATION OF CHANGE IN STREAMFLOW	OVERALL REGIONAL SENSITIVITY TO CLIMATIC VARIATION
Δ YIELD FROM UNREGULATED BASINS	increase in $\bar{Q}$ by 1.65 times	decrease in variance	little change	increase in persistence	longer high flows	increase in runoff by 1.65 times; more persistence +3
Δ YIELD FROM RESERVOIRS	increased as $\bar{Q}$ increases	increased as variance decreases	little change	increased as flows are more persistent	little change	increased as $\bar{Q}$ increases, flow less variable, shorter duration low flows +3
Δ YIELD FROM GROUND WATER SOURCES	increased as water level rises and demand falls	improved as variance in streamflow decreases	little change	improved as recharge is greater	improved yield as recharge improves	improved as recharge is increased +3
Δ QUALITY OF UNTREATED WATER	little change	little change	little change	little change	little change	little change 0
EFFECTIVENESS OF INTERBASIN AND INTERSYSTEM CONNECTIONS	little change	little change	little change	little change	little change	little change 0
ESTIMATED SYSTEM RELIABILITY	good; large storage useful	little change	little change	little change	little change	little change 0
MAGNITUDE AND CONTROL OF DEMAND	little change	little change	little change	little change	little change	little change 0
COST OF OPERATION OF WATER SYSTEMS	little change	little change	little change	little change	little change	little change 0
ABILITY OF THE WATER SYSTEM TO RESPOND TO CLIMATIC VARIATION	good; large storage prohibits flooding; some dredging for navigation	little change	little change	good; some persistent high flows may cause shortages in storage	little change	good; present large storage beneficial; may be some decline in ag. use as temp. falls +3

Appendix Table 21. Region 11, Scenario 1 (Warmer and Drier)

	INCREASE (DECREASE) IN MEAN ANNUAL STREAMFLOW	INCREASE (DECREASE) IN VARIANCE OF STREAMFLOW	INCREASE(DECREASE) SKEWNESS OF DISTRIBUTION OF STREAMFLOW	INCREASE (DECREASE) IN PERSISTENCE OF STREAMFLOW	RAPIDITY & DURATION OF CHANGE IN STREAMFLOW	OVERALL REGIONAL SENSITIVITY TO CLIMATIC VARIATION
Δ YIELD FROM UNREGULATED BASINS	decrease in mean annual runoff by 50 to 60 percent from present	increase in variance of streamflow as baseflow becomes less	increase in skewness as number of low flows increase	decrease in persistence as baseflow decreases	increase in duration of low flows	large decrease in mean annual flow; incr. in variance & duration of low flows, incr. in persistence -4
Δ YIELD FROM RESERVOIRS	tremendous decrease with small reservoirs ineffective	decrease in yield as variance increases	decrease in yield as skewness increases	decrease in yield as persistence decreases	decrease in yield as low flows increase	yield from reserv. much reduced as mean flow & other parameters are changed -4
Δ YIELD FROM GROUND WATER SOURCES	decreased because of decrease recharge and increased pumpage	decreased as variance increases	little effect	decreased as flow persistence decreases	decreased as low flow is longer duration	major decr. in ground water yield as recharge is much less & pumpage is much greater -4
Δ QUALITY OF UNTREATED WATER	deterioration; present salty water in lower region would become much worse	poorer quality as variance increases	poor quality as skewness increases	poor quality as persistence of flow is less	poor quality as low flow duration is greater	major deterioration of quality; salinity much higher especially in lower region -4
EFFECTIVENESS OF INTERBASIN AND INTERSYSTEM CONNECTIONS	some help for water shortages but probably not enough	may help to dampen some of increase in variance	may help in decreasing numbers of no flows and high flows	may help in providing a more consistent flow	may help during long low flow periods	interbasin diversions may be useful but probably not of large magnitude -3
ESTIMATED SYSTEM RELIABILITY	unreliable with most of region experiencing severe water shortages and/or water salanity problems	probably unable to cope with increase in variance	little effect	less consistencey in flow causes system to be less reliable	longer duration of low flows causes serious system unreliability	poor system reliability because of smaller average flow and less consistent flow -3
MAGNITUDE AND CONTROL OF DEMAND	increased demand as ppt. decreases ; incr. use of ground water causing more mining	demand is higher as variance increases	little effect	demand increases as persistence (consistency) of flow is less	demand will increase as ppt. declines and low flows are longer	great incr. in demand as ppt. is less and ET is more ground water use increases -4
COST OF OPERATION OF WATER SYSTEMS	large increase as modification are made; more wells drilled	large increase as changes are made to accomodate increase in variance	increased as skewness causes need for larger storage	increased as lack of persistence causes need for larger storage	longer duration of low flows causes need for greater storage	large inc. for additional surface storage & conjunctive use of ground water -4
ABILITY OF THE WATER SYSTEM TO RESPOND TO CLIMATIC VARIATION	poor; water shortages severe, interbasin transfer of little help water quality bad in lower region	system unable to cope with increase in variance	increase in skewness causes parts of the system to be inadequate	less consistent flows causes some system failure	longer low flows cause poor system response	regional system is unable to respond; water shortage; salinity, major problems -4

Appendix Table 22. Region 11, Scenario 2 (Cooler and Wetter)

	INCREASE (DECREASE) IN MEAN ANNUAL STREAMFLOW	INCREASE (DECREASE) IN VARIANCE OF STREAMFLOW	INCREASE(DECREASE) SKEWNESS OF DISTRIBUTION OF STREAMFLOW	INCREASE (DECREASE) IN PERSISTENCE OF STREAMFLOW	RAPIDITY & DURATION OF CHANGE IN STREAMFLOW	OVERALL REGIONAL SENSITIVITY TO CLIMATIC VARIATION
Δ YIELD FROM UNREGULATED BASINS	increase in mean annual flows of 1.8 to 2.0 times present	decrease in variance as flows are more consistent	little change	increased persistence as baseflow is greater	longer duration of high flows	incr. in mean annual flow of near 2.0 times present; flows more consist. +4
Δ YIELD FROM RESERVOIRS	increase in reservoir yield; flooding of low lands increased	yield increased as flow is more consistent	little change	increased yield as baseflow is greater	yield is increased as more high flows	incr. yield as mean is greater, & flow is more consistent +4
Δ YIELD FROM GROUND WATER SOURCES	increased as recharge is much higher; ppt. more; ET less	increased as surface flow is less variable	little change	increased as flow is more consistent	longer duration of high flows makes yield greater	yield from ground water much greater as recharge is much more +4
Δ QUALITY OF UNTREATED WATER	improved as mean flow is higher and tends to remove salts	improved as flows are less variable	little change	improved as flows are more persistent	improved as high flows tend to "flush" the system	quality is much improved as flow is greater & salinity is less +4
EFFECTIVENESS OF INTERBASIN AND INTERSYSTEM CONNECTIONS	little change	little change	little change	little change	little change	little change 0
ESTIMATED SYSTEM RELIABILITY	good; some additional flood protection for low lands in lower region	little change	little change	little change	longer duration of high flows will cause flooding of low lands	good; flooding of low lands in lower region major pblm. +2
MAGNITUDE AND CONTROL OF DEMAND	little change	little change	little change	little change	little change	little change 0
COST OF OPERATION OF WATER SYSTEMS	little change	little change	little change	little change	little change	little change 0
ABILITY OF THE WATER SYSTEM TO RESPOND TO CLIMATIC VARIATION	good; ag.much helped; reduction of ground water mining; some flooding of low lands in the lower region	little change	little change	increased persistence is helpful in overall consistency of water supply	longer duration of high flows causes flooding but also improves quality	good; ag. uses much improved; quality improved; some flooding +3

Appendix Table 23. Region 12, Scenario 1 (Warmer and Drier)

	INCREASE (DECREASE) IN MEAN ANNUAL STREAMFLOW	INCREASE (DECREASE) IN VARIANCE OF STREAMFLOW	INCREASE (DECREASE) SKEWNESS OF DISTRIBUTION OF STREAMFLOW	INCREASE (DECREASE) IN PERSISTENCE OF STREAMFLOW	RAPIDITY & DURATION OF CHANGE IN STREAMFLOW	OVERALL REGIONAL SENSITIVITY TO CLIMATIC VARIATION
Δ YIELD FROM UNREGULATED BASINS	decrease in present mean annual runoff by 50 percent	increase in variance	increase in skewness	decrease in persistence as baseflow decreases	longer duration of low flows	reduction in mean annual runoff by 50 percent; less consistency in flow; longer low flows -4
Δ YIELD FROM RESERVOIRS	decrease as mean annual flow decreases	decrease as variability increases	decreases as skewness increases	decreases as persistence decreases	decreases as longer low flows occur	reduced reserv. yield as inflow is less, more variable & less consistent -4
Δ YIELD FROM GROUND WATER SOURCES	decreases in yield as recharge is less and ppt. decreases, ET increases	little effect except in stream-connected aquifers	little effect	decreases in persistence makes less recharge and greater usage of ground water	longer duration of low flows causes greater use of ground water	yield from aquifers lower as streamflow is less; direct recharge is less & ET higher -4
Δ QUALITY OF UNTREATED WATER	deterioration; salinity increases as $\bar{Q}$ decreases	little change	salinity increases as skewness increases	salinity increases as persistence (baseflow) decreases	salinity increases as duration of low flows increase	quality decreases as mean flow decr., skewness incr., persistence decr. -4
EFFECTIVENESS OF INTERBASIN AND INTERSYSTEM CONNECTIONS	may be effective alleviating local shortages	may be effective in some parts of region in reducing variability	little change	may help in making flow more consistent	may help in long duration low flow periods	overall effectiveness reduced but may cushion input -2
ESTIMATED SYSTEM RELIABILITY	generally unreliable as water shortages occur	increases variability causes poor system response	increased skewness causes poor operation of system	decrease in baseflow (persist.) creates many problems but system may be unreliable	longer duration of low flows causes unreliability	decr. reliability as system comes -4 under stress; incr. demand, decr. supply
MAGNITUDE AND CONTROL OF DEMAND	increase in demand, conjunctive use of ground water necessary	increase in magnitude as variability incr.	magnitude increases as low flows predominate	magnitude increases as low baseflow creates unreliability	magnitude of demand increases as low flows are longer	incr. demand causes general system failure with incr. stress on ground water source -4
COST OF OPERATION OF WATER SYSTEMS	increases as modifications become necessary	increased as modification are made to smooth increased variability	cost increases as low flows predominate	increased as operations are changed to cope with unreliability	cost increases as measures are taken to diminish duration of low flows	cost increased as changes are implemented -4
ABILITY OF THE WATER SYSTEM TO RESPOND TO CLIMATIC VARIATION	poor; large usage at present does not leave room for any reductions	poor; increased variability makes surface storage inadequate	poor; increase in skewness makes surface inadequate	poor; decrease in baseflow causes high unreliability	poor; longer low flows create system unreliability	poor; incr. demand, decr. supply; incr. stress on ground water, deterioration of quality -4

Appendix Table 24. Region 12, Scenario 2 (Cooler and Wetter)

	INCREASE (DECREASE) IN MEAN ANNUAL STREAMFLOW	INCREASE (DECREASE) IN VARIANCE OF STREAMFLOW	INCREASE(DECREASE) SKEWNESS OF DISTRIBUTION OF STREAMFLOW	INCREASE (DECREASE) IN PERSISTENCE OF STREAMFLOW	RAPIDITY & DURATION OF CHANGE IN STREAMFLOW	OVERALL REGIONAL SENSITIVITY TO CLIMATIC VARIATION
Δ YIELD FROM UNREGULATED BASINS	increase in mean annual runoff to near 2.0 times present runoff	decrease as baseflow becomes more consistent	decrease in skewness as flow is more consistent	increase in persistence as baseflow increases	longer duration of high flows	incr. in mean by 2.0 times; decr. in variability & more consistent flow +4
Δ YIELD FROM RESERVOIRS	increased as mean annual flow increases	some increase as input flow is less variable	little change	increase in yield as higher flows are more persistent	increased as higher flows are more dominant	increase in reserv. yield as mean input incr. and is more consistent +4
Δ YIELD FROM GROUND WATER SOURCES	increase as recharge increases and demand increases	little change	little change	some additional yield as flows are more persistent	higher flow increases recharge increasing yield	higher ground water yields as usage decr. and recharge incr. +4
Δ QUALITY OF UNTREATED WATER	improved as higher flow flushes system	improved as flows are more consistent	little change	improved as baseflow is greater	improved as higher flow flushes system	improved quality; less salinity as higher flows are predominant +4
EFFECTIVENESS OF INTERBASIN AND INTERSYSTEM CONNECTIONS	little change	little change	little change	little change	little change	little change 0
ESTIMATED SYSTEM RELIABILITY	little change, some flooding may occur	little change	little change	little change	little change	some additional flood control may be necessary +1
MAGNITUDE AND CONTROL OF DEMAND	decrease as usage is less	little change	little change	little change	little change	magnitude of demand decreases as less water is used +3
COST OF OPERATION OF WATER SYSTEMS	some increase as flood control required	little change	little change	little change	little change	some incr. as additional flood control necessary -2
ABILITY OF THE WATER SYSTEM TO RESPOND TO CLIMATIC VARIATION	good; some flooding of low lands	good; flow less variable	good as flow is less skewed	good as baseflow increases	good as high flows become more prevalent; some flooding	good; additional flood control may be necessary especially in low region +3

Appendix Table 25. Region 13, Scenario 1 (Warmer and Drier)

	INCREASE (DECREASE) IN MEAN ANNUAL STREAMFLOW	INCREASE (DECREASE) IN VARIANCE OF STREAMFLOW	INCREASE(DECREASE) SKEWNESS OF DISTRIBUTION OF STREAMFLOW	INCREASE (DECREASE) IN PERSISTENCE OF STREAMFLOW	RAPIDITY & DURATION OF CHANGE IN STREAMFLOW	OVERALL REGIONAL SENSITIVITY TO CLIMATIC VARIATION
Δ YIELD FROM UNREGULATED BASINS	a decrease in present mean annual runoff by 75%	some increase in variance possible but it is already large	already highly skewed, little change would be expected	present trend is large may not change appreciably	some increase in low flow duration probable	decrease in mean annual flow to 75% of present flow ; some longer low flows -4
Δ YIELD FROM RESERVOIRS	decrease by large amount because of decrease in inflow	little change	little change	little change	longer duration low flows cause additional decrease in yield	decrease in yield as annual inflow decr. & duration of low flows incr. -4
Δ YIELD FROM GROUND WATER SOURCES	decreases as recharge from surface flow decreases	little change	little change	little change	little change	decreases as recharge decreases & use increases -4
Δ QUALITY OF UNTREATED WATER	deteriorates as flow diminishes	little change	little change	little change	little change	quality becomes more saline as flow diminishes -4
EFFECTIVENESS OF INTERBASIN AND INTERSYSTEM CONNECTIONS	effective if can offset diminishing flow	little change	little change	little change	little change	somewhat effective but not large enough to offset reduced flow -2
ESTIMATED SYSTEM RELIABILITY	system generally unreliable as flows are reduced	little change	little change	little change	little change	very poor- no additional sources of water; presently used at max. rate -4
MAGNITUDE AND CONTROL OF DEMAND	large increase in demand as precipitation decreases and ET incr.; incr. use of ground water	little change	little change	little change	little change	large incr. in demand as ppt. decr. & ET incr.; some add. use of ground water helpful -3
COST OF OPERATION OF WATER SYSTEMS	large increase as modifications are needed	little change	little change	little change	little change	large increase as modifications are attempted -4
ABILITY OF THE WATER SYSTEM TO RESPOND TO CLIMATIC VARIATION	poor; interbasin diversions inadequate; presently using all available water	little change	little change	little change	little change	very poor; region wide shortage in already stressed system -4

Appendix Table 26. Region 13, Scenario 2 (Cooler and Wetter)

	INCREASE (DECREASE) IN MEAN ANNUAL STREAMFLOW	INCREASE (DECREASE) IN VARIANCE OF STREAMFLOW	INCREASE(DECREASE) SKEWNESS OF DISTRIBUTION OF STREAMFLOW	INCREASE (DECREASE) IN PERSISTENCE OF STREAMFLOW	RAPIDITY & DURATION OF CHANGE IN STREAMFLOW	OVERALL REGIONAL SENSITIVITY TO CLIMATIC VARIATION
Δ YIELD FROM UNREGULATED BASINS	increase in mean annual runoff by 1.8 times above present	less variable flow as flows are more consistent and greater	decrease in skewness as low flows are less	decrease in persistence as trend is changed	longer duration of flow as baseflow is improved	increase in mean runoff by 1.8 times decrease in skew, variability & persistence (trend) +4
Δ YIELD FROM RESERVOIRS	increase in yield as inflow increases and evaporation decreases	decrease in variance; yields increased as flows are more consistent, less variable	decrease in skew, yield increased as higher flows are more dominant	decrease in trend; yields increase	increased duration of high flows, increased yields	large incr. in net yields; flood storage may be inadequate +3
Δ YIELD FROM GROUND WATER SOURCES	increased as recharge increases; less demand as surface water is more available	increased as flows are less variable	increased as skewness is less (higher flows predominate)	increased as persistence (trend) is diminished	increased as surface flows are higher	incr. in yield from ground water as recharge is greater & demand on ground water is less +4
Δ QUALITY OF UNTREATED WATER	improved; salinity greatly diminished	improved as flows are less variable	improved as higher flows predominate	improved as downward trend in surface flow is reversed	improved as higher flows are longer in duration	water quality improved over region, less salinity +4
EFFECTIVENESS OF INTERBASIN AND INTERSYSTEM CONNECTIONS	little change	little change	little change	little change	little change	little change 0
ESTIMATED SYSTEM RELIABILITY	good; flooding of low lands possible	good; surface storage may be small	little change	little change	some shortage in surface storage to handle lower flows	good; shortage of surface water storage; some flooding +3
MAGNITUDE AND CONTROL OF DEMAND	little change	little change	little change	little change	little change	little change 0
COST OF OPERATION OF WATER SYSTEMS	some increase if flood control is needed	little change	little change	little change	some increase if high flows cause flood problems	some incr. if flood control & channelization needed +2
ABILITY OF THE WATER SYSTEM TO RESPOND TO CLIMATIC VARIATION	good; some improved flood control necessary; channelization necessary	good; some additional fllod control needed	little change	little change	additional flood control may be needed for longer high flows	good; additional flood control: channelization +3

Appendix Table 27. Region 14, Scenario 1 (Warmer and Drier)

	INCREASE (DECREASE) IN MEAN ANNUAL STREAMFLOW	INCREASE (DECREASE) IN VARIANCE OF STREAMFLOW	INCREASE(DECREASE) SKEWNESS OF DISTRIBUTION OF STREAMFLOW	INCREASE (DECREASE) IN PERSISTENCE OF STREAMFLOW	RAPIDITY & DURATION OF CHANGE IN STREAMFLOW	OVERALL REGIONAL SENSITIVITY TO CLIMATIC VARIATION
Δ YIELD FROM UNREGULATED BASINS	decrease in mean annual flow to 65 percent of present	increase in variance of streamflow	some increase in skew as low flows are more common	decrease in persistence as baseflow declines	longer duration of low flows	35 % reduction in present mean flow; more variable, less persistence in flow -4
Δ YIELD FROM RESERVOIRS	decreases as mean flow decreases	decreases as flows are more variable	decreases as skew increases	decreases as flows are less consistent	decreases as low flows are longer duration	general decr. in reserv. yield as inflows are less & less consistent -4
Δ YIELD FROM GROUND WATER SOURCES	decrease as recharge from surface flow is less; greater use as surface flow declines	little change	little change	less contribution as baseflow declines	longer low flows detrimental to recharge along streams	general decline as recharge is less & usage increases -3
Δ QUALITY OF UNTREATED WATER	rise in salinity as mean flow declines	little change	little change	decline in baseflow causes salinity build up	longer duration of low flows cause severe salinity increases	salinity incr. as mean flow decr. & low flows are longer in duration -4
EFFECTIVENESS OF INTERBASIN AND INTERSYSTEM CONNECTIONS	exports from the basin could be reduced as supply is reduced	little effect	little effect	lower baseflow and availability causes reduction in exports	longer low flows reduces water supply for exports.	general water shortages makes water unavailable for export -4
ESTIMATED SYSTEM RELIABILITY	poor; as system is currently stressed as water is over appropriated	little effect	little effect	little effect	longer duration low flows put additional stress on system	system poor as present supply is over appropriated; red. of 35% causes legal & economic pblms.-4
MAGNITUDE AND CONTROL OF DEMAND	large increase in demand as ppt. is less and ET increases; conjunctive use of ground water for control	little effect	little effect	little effect	little effect	large incr. in demand; conjunctive use of ground water ease some shortage -4
COST OF OPERATION OF WATER SYSTEMS	increased as needed modifications are implemented	little effect	little effect	little effect	little effect	general incr. in cost & modification are made to meet shortages; incr. -3 use of ground water
ABILITY OF THE WATER SYSTEM TO RESPOND TO CLIMATIC VARIATION	poor; present supply is fully used; incr. use of ground water some help	poor; increase in variability causes need for additional storage	poor; increase in skew makes present storage inadequate	less consistent flows causes increase in salinity	longer duration of low flows cause shortages, salinity problems	poor; additional stress on system already stressed; -4 water shortages & poor quality result

Appendix Table 28. Region 14, Scenario 2 (Cooler and Wetter)

	INCREASE (DECREASE) IN MEAN ANNUAL STREAMFLOW	INCREASE (DECREASE) IN VARIANCE OF STREAMFLOW	INCREASE(DECREASE) SKEWNESS OF DISTRIBUTION OF STREAMFLOW	INCREASE (DECREASE) IN PERSISTENCE OF STREAMFLOW	RAPIDITY & DURATION OF CHANGE IN STREAMFLOW	OVERALL REGIONAL SENSITIVITY TO CLIMATIC VARIATION
Δ YIELD FROM UNREGULATED BASINS	increase in mean annual flow by 2.0 times present	little change	little change	more consistent flow as baseflow increases	longer duration of high flows	yield incr. by 2.0 times present; flow more consistent as baseflow incr. +4
Δ YIELD FROM RESERVOIRS	increases as inflows are greater and more consistent	little effect	little effect	greater yield as flows are more consistent as baseflows are higher	longer duration of high flows increases yields	general incr. in reserv. yield as inflows are greater & more consistent +4
Δ YIELD FROM GROUND WATER SOURCES	some increase but little need as surface water supply is greater	little change	little change	little change	little change	ground water is used little at present & would not be needed if surface supply doubled +1
Δ QUALITY OF UNTREATED WATER	some improvement in salinity as greater flow causes dilution	little change	little change	little change	little change	salinity is less as increased flow "flushes" system +4
EFFECTIVENESS OF INTERBASIN AND INTERSYSTEM CONNECTIONS	exports might increase if supply was more abundant	little change	little change	little change	little change	pressure for increased exports as supply increases -1
ESTIMATED SYSTEM RELIABILITY	good;additional flood control may be needed	little change	little change	little change	little change	good; some added flood protection may be needed +3
MAGNITUDE AND CONTROL OF DEMAND	increased demand as supply increases	little change	little change	little change	little change	increased demand as supply increases +2
COST OF OPERATION OF WATER SYSTEMS	some increase as demand increases and additional flood conrol is necessary	little effect	little effect	little effect	little effect	incr. as demand increases & as additional flood control is necessary -2
ABILITY OF THE WATER SYSTEM TO RESPOND TO CLIMATIC VARIATION	good; some additional flood control may be needed	little change	little change	little change	little change	good; larger storage necessary for incr. demand & for flood control +3

Appendix Table 29. Region 15, Scenario 1 (Warmer and Drier)

	INCREASE (DECREASE) IN MEAN ANNUAL STREAMFLOW	INCREASE (DECREASE) IN VARIANCE OF STREAMFLOW	INCREASE(DECREASE) SKEWNESS OF DISTRIBUTION OF STREAMFLOW	INCREASE (DECREASE) IN PERSISTENCE OF STREAMFLOW	RAPIDITY & DURATION OF CHANGE IN STREAMFLOW	OVERALL REGIONAL SENSITIVITY TO CLIMATIC VARIATION
Δ YIELD FROM UNREGULATED BASINS	decrease by 45 percent in present mean annual flow	little change from present	little change from present	little change from present	little change from present	decr. in present mean annual flow by 45%; little change in variance & consistency of flow -4
Δ YIELD FROM RESERVOIRS	decreases as inflow decreases; smaller reservoirs dry, larger reservoirs effected by greater evaporation	little change from present	little change from present	little change from present	little change from present	large decr. in reserv. yield as inflow is reduced & evaporation is increased -4
Δ YIELD FROM GROUND WATER SOURCES	reduced as recharge from streams is reduced; ET increased; demand increased	little change from present	little change from present	little change from present	little change from present	reduction in ground water yield as recharge is less; ET incr.; demand incr. -4
Δ QUALITY OF UNTREATED WATER	salinity increased as water level declines and surface water is less	little change from present	little change from present	little change from present	little change from present	general deterioration of quality; salinity increases -4
EFFECTIVENESS OF INTERBASIN AND INTERSYSTEM CONNECTIONS	change is so large, interbasin connections generally ineffective	little change from present	little change from present	little change from present	little change from present	large change in water availability makes interbasin connections ineffective -4
ESTIMATED SYSTEM RELIABILITY	poor as system is already stressed; water shortages and water quality deterioration common	little change from present	little change from present	little change from present	little change from present	system reliability poor as already stressed -4
MAGNITUDE AND CONTROL OF DEMAND	large demand increase with greater pumping from ground water	little change from present	little change from present	little change from present	little change from present	large incr. in demand; ground water used more extensively where possible -4
COST OF OPERATION OF WATER SYSTEMS	increased cost as modifications are made	little change from present	little change from present	little change from present	little change from present	increased cost as remedial measures are attempted -3
ABILITY OF THE WATER SYSTEM TO RESPOND TO CLIMATIC VARIATION	poor; little room for reduced supply; ground water mining already excessive	little change from present	little change from present	little change from present	little change from present	water system presently stressed; ability to respond to climatic change extremely poor -4

Appendix Table 30. Region 15, Scenario 2 (Cooler and Wetter)

	INCREASE (DECREASE) IN MEAN ANNUAL STREAMFLOW	INCREASE (DECREASE) IN VARIANCE OF STREAMFLOW	INCREASE(DECREASE) SKEWNESS OF DISTRIBUTION OF STREAMFLOW	INCREASE (DECREASE) IN PERSISTENCE OF STREAMFLOW	RAPIDITY & DURATION OF CHANGE IN STREAMFLOW	OVERALL REGIONAL SENSITIVITY TO CLIMATIC VARIATION
Δ YIELD FROM UNREGULATED BASINS	increase in mean annual runoff by 1.7 times present	some changes in variance as flows become more consistent	some decrease in skew as zero flow days are less	some increase in persistence as basflow occurs	more consistent flow as baseflow increases	incr. in mean annual flow by 1.7 times; flow less variable; more consistent +4
Δ YIELD FROM RESERVOIRS	increase as inflow is increased and variability less and evaporation is less as temperature declines	some increase as variability less	some increase as zero flow days are less	some increase as baseflow increases	little change	incr. reserv. yield as inflow is greater & evaporation is less +4
Δ YIELD FROM GROUND WATER SOURCES	increased as recharge is greater from streamflow	increased as surface flow becomes less variable	little change	little change	little change	incr. as surface flows create more recharge, less reliance on ground water +4
Δ QUALITY OF UNTREATED WATER	improved as salinity is less	little change from present	little change from present	improved as baseflow is greater	little change	improved quality as larger surface flows remove salts +4
EFFECTIVENESS OF INTERBASIN AND INTERSYSTEM CONNECTIONS	little change from present	little change from present	little change from present	little change from present	little change from present	little change from present 0
ESTIMATED SYSTEM RELIABILITY	good; additional flood control may be needed although present storage is large	little change from present	little change from present	little change from present	little change from present	good; present reserv. capacity is large & should be adeq.;some add. flood protect. may be necessary +2
MAGNITUDE AND CONTROL OF DEMAND	little change from present	little change from present	little change from present	little change from present	little change from present	little change from present 0
COST OF OPERATION OF WATER SYSTEMS	little change from present	little change from present	little change from present	little change from present	little change from present	little change from present 0
ABILITY OF THE WATER SYSTEM TO RESPOND TO CLIMATIC VARIATION	good; present large storage helpful; some add. flood control needed; surface usage incr.; g.w. demand decr	good; decrease in variability helpful	good; decr. in skew and increase in flow consistency helpful	good; increased baseflow makes more surface water available locally	longer duration of high flows and large baseflows increase water availability	good; present large storage useful; some add. flood protection necessary +4

Appendix Table 31. Region 16, Scenario 1 (Warmer and Drier)

	INCREASE (DECREASE) IN MEAN ANNUAL STREAMFLOW	INCREASE (DECREASE) IN VARIANCE OF STREAMFLOW	INCREASE(DECREASE) SKEWNESS OF DISTRIBUTION OF STREAMFLOW	INCREASE (DECREASE) IN PERSISTENCE OF STREAMFLOW	RAPIDITY & DURATION OF CHANGE IN STREAMFLOW	OVERALL REGIONAL SENSITIVITY TO CLIMATIC VARIATION
Δ YIELD FROM UNREGULATED BASINS	decrease in mean annual flow to 55 percent of present	little change from present	little change from present	little change from present	little change from present	decrease of mean annual flow to 55 percent of present -3
Δ YIELD FROM RESERVOIRS	decreased as mean inflow changes	little change from present	little change from present	little change from present	little change from present	decr. in reserv. yield as mean inflow decr. but small storage cap. has little overall effect -3
Δ YIELD FROM GROUND WATER SOURCES	decrease as recharge decreases; some increase in use as surface supply is less	little change from present	little change from present	little change from present	little change from present	decr. in water level some decr. in yield as recharge declines incr. of g.w. use as surface water is less -2
Δ QUALITY OF UNTREATED WATER	little change from present	little change from present	little change from present	little change from present	little change from present	little change from present 0
EFFECTIVENESS OF INTERBASIN AND INTERSYSTEM CONNECTIONS	little change from present	little change from present	little change from present	little change from present	little change from present	little change from present 0
ESTIMATED SYSTEM RELIABILITY	little change from present	little change from present	little change from present	little change from present	little change from present	little change from present 0
MAGNITUDE AND CONTROL OF DEMAND	little change from present	little change from present	little change from present	little change from present	little change from present	little change from present 0
COST OF OPERATION OF WATER SYSTEMS	little change from present	little change from present	little change from present	little change from present	little change from present	little change from present 0
ABILITY OF THE WATER SYSTEM TO RESPOND TO CLIMATIC VARIATION	excellent; no stress on system at present; large g.w. reserv. to supplement any local surface water shortages	little change from present	little change from present	little change from present	little change from present	excellent; current water use is not excessive as to supply; some increase in g.v. use may be needed -2

Appendix Table 32. Region 16, Scenario 2 (Cooler and Wetter)

	INCREASE (DECREASE) IN MEAN ANNUAL STREAMFLOW	INCREASE (DECREASE) IN VARIANCE OF STREAMFLOW	INCREASE(DECREASE) SKEWNESS OF DISTRIBUTION OF STREAMFLOW	INCREASE (DECREASE) IN PERSISTENCE OF STREAMFLOW	RAPIDITY & DURATION OF CHANGE IN STREAMFLOW	OVERALL REGIONAL SENSITIVITY TO CLIMATIC VARIATION
Δ YIELD FROM UNREGULATED BASINS	increase in mean annual flow of 1.8 times present mean	some decreases in variability	some decrease in skew	some increase in persistence as baseflow increases	longer duration of high flows	increase in mean flow by 1.8 times present; flow less variable & higher persistence +3
Δ YIELD FROM RESERVOIRS	increased; not major because of limited capacity, more reserv. needed; closed basin lakes expand	some increase as flow is more consistent (less variable)	some increase as low flows are less dominant	some increase as baseflow is greater	some increase as high flows are more dominant	increase in reservoir yield; closed basin lakes expand causing some inundation of ag. & urban lands -2
Δ YIELD FROM GROUND WATER SOURCES	little change from present	little change from present	little change from present	little change from present	little change from present	little change from present 0
Δ QUALITY OF UNTREATED WATER	little change from present	little change from present	little change from present	little change from present	little change from present	little change from present 0
EFFECTIVENESS OF INTERBASIN AND INTERSYSTEM CONNECTIONS	little change from present	little change from present	little change from present	little change from present	little change from present	little change from present 0
ESTIMATED SYSTEM RELIABILITY	some flood control ineffectiveness	some flood control ineffectiveness	some flood control ineffectiveness	some flood control ineffectiveness	longer duration high flows cause flooding	system ineffective for flood control -2
MAGNITUDE AND CONTROL OF DEMAND	little change from present	little change from present	little change from present	little change from present	little change from present	little change from present 0
COST OF OPERATION OF WATER SYSTEMS	some increase as flood control needs increase	little change from present	little change from present	little change from present	longer duration of high flows increases need for flood control	increases cost for flood control -2
ABILITY OF THE WATER SYSTEM TO RESPOND TO CLIMATIC VARIATION	good; low lands flooded; expansion of closed basin lakes; changes may be necessary	little change from present	little change from present	little change from present	high flows cause problems; system needs modifications for flood control	good; need for additional flood control; low land protection from expansion of closed basin lakes +1

Appendix Table 33. Region 17, Scenario 1 (Warmer and Drier)

	INCREASE (DECREASE) IN MEAN ANNUAL STREAMFLOW	INCREASE (DECREASE) IN VARIANCE OF STREAMFLOW	INCREASE(DECREASE) SKEWNESS OF DISTRIBUTION OF STREAMFLOW	INCREASE (DECREASE) IN PERSISTENCE OF STREAMFLOW	RAPIDITY & DURATION OF CHANGE IN STREAMFLOW	OVERALL REGIONAL SENSITIVITY TO CLIMATIC VARIATION
Δ YIELD FROM UNREGULATED BASINS	decrease in mean annual runoff to 64 percent of present runoff	some increase in variance in some watersheds	some increase in skewness in some watersheds as low flows predominat	some decrease in persistence as baseflow declines	longer duration of low flow can be expected	decrease to 65 percent of present; flows generally more variable and less persistent -3
Δ YIELD FROM RESERVOIRS	decrease in reservoir yield as inflow declines small reservoirs in upper watersheds adversely affected	increase in variance causes yields to drop	dominance of lower flows causes yield to be less	decrease in baseflow causes yield in smaller reservoirs to drop	longer low flows cause major problems for hydroelectric and fish and wildlife	decline as inflows are less; low flows are longer; hydroelectric & fish & wildlife adversely affected -4
Δ YIELD FROM GROUND WATER SOURCES	decrease as recharge is tied to surface flow; demand on ground water increases for ag. use	ground water yield is more variable as surface flows are non-variable	little effect	baseflows decline as ground water levels decline	longer low flows cause depletion of ground water by baseflow and pumpage	general decline of ground water because of close tie with surface water -4
Δ QUALITY OF UNTREATED WATER	little change from present	little change from present	little change from present	little change from present	little change from present	little change from present 0
EFFECTIVENESS OF INTERBASIN AND INTERSYSTEM CONNECTIONS	little change from present	little change from present	little change from present	little change from present	little change from present	little change from present 0
ESTIMATED SYSTEM RELIABILITY	overall fair; some problems in navigation and hydroelectric generation	little effect	little effect	little effect	longer duration low flows cause navigation, hydroelectric problems	some system unreliability in navigation & hydropower generation -2
MAGNITUDE AND CONTROL OF DEMAND	little change from present	little change from present	little change from present	little change from present	little change from present	little change from present 0
COST OF OPERATION OF WATER SYSTEMS	increased; dredging, channelization, alternate power generation	little effect	little effect	little effect	longer duration of low flows cause major problems and increase cost	general increase in cost for improved navigation; also alternate sources of power generation -3
ABILITY OF THE WATER SYSTEM TO RESPOND TO CLIMATIC VARIATION	fair to good; problems: power generation, navigation, fish & wildlife; salt water encroachment	increased variation but little effect	increased skewness but little regional effect local storage problems	decrease in baseflow causes local problems but little regional effect	longer duration low flows cause region wide pblms. of power generation, navig. salt water encroachment	system generally reliable; problems: local water shortages, power generation, navig. salt water encroachment -2

Appendix Table 34. Region 17, Scenario 2 (Cooler and Wetter)

	INCREASE (DECREASE) IN MEAN ANNUAL STREAMFLOW	INCREASE (DECREASE) IN VARIANCE OF STREAMFLOW	INCREASE(DECREASE) SKEWNESS OF DISTRIBUTION OF STREAMFLOW	INCREASE (DECREASE) IN PERSISTENCE OF STREAMFLOW	RAPIDITY & DURATION OF CHANGE IN STREAMFLOW	OVERALL REGIONAL SENSITIVITY TO CLIMATIC VARIATION
Δ YIELD FROM UNREGULATED BASINS	increase in mean annual runoff by 1.4 times present	little change from present	little change from present	little change from present	longer duration of high flows	increase in mean annual runoff by 1.4 times present; longer duration of high flows +2
Δ YIELD FROM RESERVOIRS	increased yield; storage may be inadequate for flood control	little change from present	little change from present	little change from present	longer duration high flows may make flood storage inadequate	increased reservoir yield; flood storage capacity may be inadequate +2
Δ YIELD FROM GROUND WATER SOURCES	little change from present	little change from present	little change from present	little change from present	little change from present	little change from present 0
Δ QUALITY OF UNTREATED WATER	little change from present	little change from present	little change from present	little change from present	little change from present	little change from present 0
EFFECTIVENESS OF INTERBASIN AND INTERSYSTEM CONNECTIONS	little change from present	little change from present	little change from present	little change from present	little change from present	little change from present 0
ESTIMATED SYSTEM RELIABILITY	flood control may be somewhat unreliable	little effect	little effect	little effect	little effect	some unreliablity in flood control -2
MAGNITUDE AND CONTROL OF DEMAND	little change from present	little change from present	little change from present	little change from present	little change from present	little change from present 0
COST OF OPERATION OF WATER SYSTEMS	slight increase for flood control, drainage of low lands	little effect	little effect	little effect	little effect	some increase for flood control; drainage -1
ABILITY OF THE WATER SYSTEM TO RESPOND TO CLIMATIC VARIATION	good; additional flood control necessary; drainage necessary in some low lands	little effect	little effect	little effect	longer duration of high flow could increase need for flood control	good; additional flood control; drainage of low lands may be necessary +3

Appendix Table 35. Region 18, Scenario 1 (Warmer and Drier)

	INCREASE (DECREASE) IN MEAN ANNUAL STREAMFLOW	INCREASE (DECREASE) IN VARIANCE OF STREAMFLOW	INCREASE(DECREASE) SKEWNESS OF DISTRIBUTION OF STREAMFLOW	INCREASE (DECREASE) IN PERSISTENCE OF STREAMFLOW	RAPIDITY & DURATION OF CHANGE IN STREAMFLOW	OVERALL REGIONAL SENSITIVITY TO CLIMATIC VARIATION
Δ YIELD FROM UNREGULATED BASINS	decrease in mean annual runoff to 50 percent of present	probably increase in variance with decrease in $\bar{Q}$	probable increase in skewness as low flows are more predominant	decrease in persistence as baseflow contributions are less	decrease in duration of low flows likely	large decrease in mean annual runoff; increase in variability and decrease in persistence -4
Δ YIELD FROM RESERVOIRS	decrease as mean inflows decrease	little effect	some shortage in regional total capacity	less inflow as baseflow declines; small reservoirs greatly affected	longer duration of low flows cause large decline in reservoir yield	yield of reservoir greatly declines as inflow less, and less baseflow -4
Δ YIELD FROM GROUND WATER SOURCES	decreases as principal recharge is from stream flow	little effect	little effect	decrease in baseflow reflects water level decline in aquifers	longer duration of low flows cause less recharge and decline in ground water yield	ground water yield less as stream recharge declines -4
Δ QUALITY OF UNTREATED WATER	some increase in salinity in central	little effect	little effect	decrease in baseflow causes deterioration in quality	longer low flows cause deterioration in quality	quality deteriorates as flow declines and baseflow is less -4
EFFECTIVENESS OF INTERBASIN AND INTERSYSTEM CONNECTIONS	increased effectiveness if source area is not in same climatic change	little effect	little effect	little effect	some effectiveness in times of extended low flow	interbasin and systems connection may help local shortages but regionally not much -2
ESTIMATED SYSTEM RELIABILITY	poor; present maximum use allows little room change in supply	little effect	some shortage in storage possible	less baseflow causes some unreliability	poor relaibility as low flows increase in duration	system reliability is poor as supply is halved -4
MAGNITUDE AND CONTROL OF DEMAND	increased demand by agriculture as ppt. decreases and ET rises	little effect	little effect	little effect	increase in demand as low flows cause local shortages	increased agricultural demand causes increased use of ground water supply -4
COST OF OPERATION OF WATER SYSTEMS	tremendous increase as modification (e.g. new wells) are attempted	little effect	little effect	increased cost to supplement loss of baseflow in streams	increased as steps are taken locally to overcome shortages	cost increases as supply decreases and interim measures are undertaken -4
ABILITY OF THE WATER SYSTEM TO RESPOND TO CLIMATIC VARIATION	poor; general water shortages; salt water encroachment	increase in variance would have little regional effect	increase in skewness may have incr. shortage of capacity but minor compared to decrease in $\bar{Q}$	poor; baseflow is an important source of supply in large part of region	poor; longer low flows adversely effects surface and ground water supply	general lack of system to meet this type of change -4

Appendix Table 36. Region 18, Scenario 2 (Cooler and Wetter)

	INCREASE (DECREASE) IN MEAN ANNUAL STREAMFLOW	INCREASE (DECREASE) IN VARIANCE OF STREAMFLOW	INCREASE(DECREASE) SKEWNESS OF DISTRIBUTION OF STREAMFLOW	INCREASE (DECREASE) IN PERSISTENCE OF STREAMFLOW	RAPIDITY & DURATION OF CHANGE IN STREAMFLOW	OVERALL REGIONAL SENSITIVITY TO CLIMATIC VARIATION
Δ YIELD FROM UNREGULATED BASINS	increase in mean annual runoff by 1.65 times present	less variability in local watersheds; regionally little change	some decrease in skewness	some increase in persistence as baseflow increases	longer duration of high flows	increase in mean runoff 1.65 times; less variable flow; greater baseflow +4
Δ YIELD FROM RESERVOIRS	increased as mean inflow increases	little change from present	little change from present	little change from present	little change from present	increased reservoir yield as mean flow increases greatly +4
Δ YIELD FROM GROUND WATER SOURCES	increased as recharge from streams is much increased	little change from present	little change from present	little change from present	little change from present	great increase in ground water yield as stream recharge greatly increases +4
Δ QUALITY OF UNTREATED WATER	some increase as system is "flushed"	little change from present	little change from present	little change from present	little change from present	improved quality of water as system is "flushed" +3
EFFECTIVENESS OF INTERBASIN AND INTERSYSTEM CONNECTIONS	little change from present unless change is regionally uniform	little change from present	little change from present	little change from present	little change from present	little change unless climatic change is regionally uniform 0
ESTIMATED SYSTEM RELIABILITY	good; additional flood control storage may be needed; drainage of low lands necessary	little change from present	little change from present	little change from present	little change from present	good system reliability additional flood control necessary; drainage of low lands +3
MAGNITUDE AND CONTROL OF DEMAND	some decline for agricultural uses	little change from present	little change from present	little change from present	little change from present	some decline in demand for agricultural purposes +3
COST OF OPERATION OF WATER SYSTEMS	some increase for flood control	little change from present	little change from present	little change from present	little change from present	slight increase for flood control and drainage of low lands +1
ABILITY OF THE WATER SYSTEM TO RESPOND TO CLIMATIC VARIATION	good; some additional storage may be needed	little change from present	little change from present	little change from present	little change from present	regional response is positive with some additional flood and drainage problems +3